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Accelerating Transition to Production by Manufacturing Readiness Focus During Development

William K. Duncan

ACCELERATING TRANSITION TO PRODUCTION BY MANUFACTURING READINESS FOCUS DURING DEVELOPMENT

THESIS

William K Duncan, Associate Director, Raytheon Technologies

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Abstract

The Department of Defense has adopted management tools, such as Manufacturing Readiness Levels (MRLs), which seek to address issues that have delayed the transition to production and delivery of deployment-ready systems. The MRL scale and assessment process institutes periodic reviews of products during the acquisition process. Specifically, MRLs provide a scale to measure, and importantly communicate, progress by evaluating and summarizing multiple aspects of product maturity. Unfortunately, issues are often identified during the periodic assessments which, if addressed earlier, would have further streamlined product delivery. The current research applies Model Based System Engineering tools to analyze and refine organizational structures and the product development process in an attempt to streamline this process. The model includes roles and artifacts involved in transferring requirements and information from design to manufacturing and the process that is applied to convert the Technical Data Package into manufactured components and assemblies. A process for actively tracking information necessary during MRL assessments to provide insight to MRL attainment on a more continuous basis is suggested to improve communication and accelerate the transition to production where appropriate.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor for his guidance and support throughout the course of this thesis effort. The insight and experience were certainly appreciated.

I would also like to thank my sponsor, Raytheon Technologies and the leadership team of the Electronic Warfare Systems (EWS) business unit of the Raytheon Intelligence and Space (RIS) division for both the financial support and latitude in job assignments provided to me facilitating this endeavor. They provided me the opportunity to work in unique roles that allowed my focus on the development of processes and team members, while meeting program and customer commitments.

William K. Duncan

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The 2018 National Defense Strategy (NDS) emphasizes the warfighter need for capabilities, delivered from new, upgraded and/or sustained systems, at the "Speed of Relevance". Here is an excerpt from that strategy:

> *"Streamline rapid, iterative approaches from development to fielding. A rapid, iterative approach to capability development will reduce costs, technical obsolescence, and acquisition risk. The Department will realign incentive and reporting structures to increase speed of delivery, enable design tradeoffs in the requirements process, expand the role of warfighters and intelligence analysis throughout the acquisition process, and utilize non-traditional suppliers. Prototyping and experimentation should be used prior to defining requirements and commercial-off-the-shelf systems. Platform electronics and software must be designed for routine replacement instead of static configurations that last more than a decade. This approach, a major departure from previous practices and culture, will allow the Department to more quickly respond to changes in the security environment and make it harder for competitors to offset our systems."*

In line with this strategy, the U.S. Air Force 2030 Science and Technology Strategy has the following Call to Action:

> "*…This Strategy secures the Air Force's continued technological advantage over rapidly developing state competitors in 2030 and beyond in support of the National Defense Strategy. It focuses research in multidisciplinary directions to enable that advantage and paves the way to convert new technologies into transformational warfighting concepts. It makes important changes to science and technology management at the headquarters and laboratory levels to more effectively develop those concepts and support their transition into the future force…*"

In light of this strategy and environment, businesses in the defense industry must find ways to accelerate all aspects of the product lifecycle from product design to production to sustainment and identify new ways to significantly reduce cycle times.

I. Background

Fielding advanced technology to provide war fighter advantage often incurs budget and schedule overruns due to unforeseen circumstances. Therefore, each program must assess risks and opportunities to balance the three major dimensions of cost, time, and functionality to appropriately apply its limited resources at the most appropriate time (DAG, 2018). A well-executed project employs its resources throughout the program life-cycle to reduce the risks over time through the completion of scheduled tasks. Unfortunately, the opportunities to reduce cost, improve functionality, and reduce program time also decrease with the passage of time.

Tracking the program cost versus budget, and time spent versus the schedule, are relatively straight forward. However, tracking the project's progress towards requirements attainment is not as simple. As there are often complex interactions among the various methods used to attain the requirements as exemplified in the Quality Function Deployment (QFD) for House of Quality, which provides a design strategy to balance the distribution of resources across the various activities which seek to impact the requirements (Johnson, 2016).

It is important to measure progress in requirements attainment, cost, and schedule as the design is matured over program phases. These phases span time as the products transition from the product concept phase into production and deployment. Successful programs deploy stable items into service to fulfill its purpose, thereby accomplishing its part of the mission.

What is the Current Solution?

To measure progress the Department of Defense (DoD) has adopted management tools which seek to address significant issues which have arisen during previous programs. For example, the adoption of "bleeding edge" technology, i.e., technology which is new and not well understood, is a common source of schedule and cost overruns. Compensation efforts has led to the development of the Technical Readiness Level (TRL) scales and assessment methods (Azizian, Mazzuchi, Sarkani, & Rico, 2011). Another issue which commonly leads to program delays is the transition of equipment designs to manufacturing, which has led to the development of the MRL scale and assessment process (OSD Manufacturing Technology Program, 2020).

Both tools provide a scale by which to measure, and importantly communicate, progress by evaluating and summarizing multiple aspects program maturity. The Technical Maturity is actually the first area of assessment for the MRL scale. It references the TRL maturity scale, and by definition states that the MRL cannot be any more mature than the TRL of the item being assessed. Although not stated explicitly in the MRL Deskbook as a limitation, there is essentially a corollary that the TRL cannot lead the MRL by large margins as a design cannot be evaluated, verified, or validated against the requirements, until the design can be manufactured. Achieving higher TRL levels requires the manufacturing and test of units from a stable process, regardless of its cost and efficiency.

What are the deficiencies with this solution?

The application of TRL and MRL assessments often fail to deliver product development lifecycles which utilize resources to balance the three dimensions of cost, time, and requirements attainment. Instead issues often arise which are associated with timing, resources, and countermeasure implementation.

Issues with timing can arise from the fact that TRL and MRL assessments are mandated only at key milestones of a project. For example, these assessments are required at the System Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR), or Test Readiness Review (TRR) milestones as seen in Figure 1. Not shown is the length of time between these reviews. For complex systems these reviews may be separated by many months or years. As a result, individuals are incentivized to delay the assessment, if possible, to provide the maximum time available to advance the maturity level prior to being scored. Delaying such assessments can result in deficiencies being latent and undiscovered until late in the lifecycle, where these deficiencies are more costly to address and have a greater chance of impacting the overall schedule. Although there is no reason why assessments could not be planned early in the life-cycle to establish a baseline with known issues to address within the Work Breakdown Structure of the project, the current processes do not incentivize such an assessment.

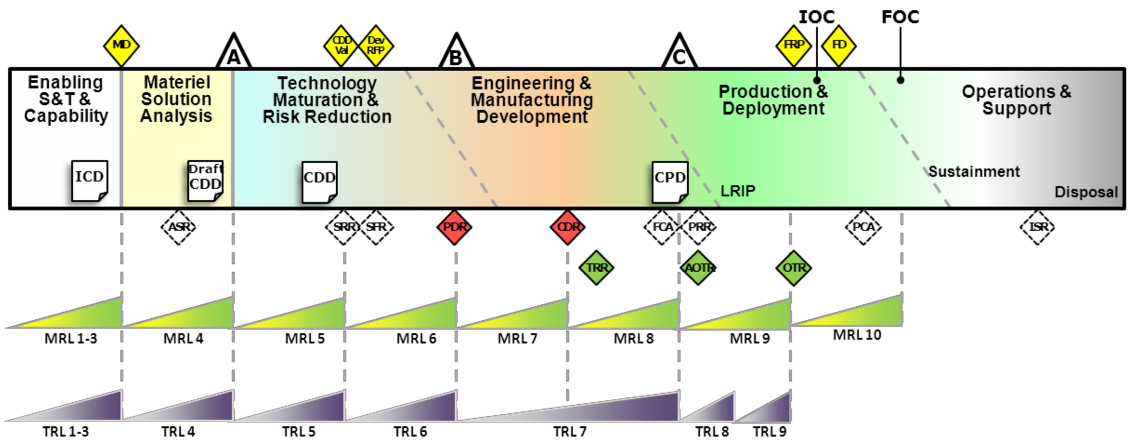


Figure 1 - Relationship of MRLs to Decision Points, Milestones, Technical Reviews, and TRLs (OSD Manufacturing Technology Program, 2020)

As details of manufacturing cannot be finalized until the technical product is fully developed, manufacturing resources are often limited during the early stages of the development process. Further, as members of the design community often have limited experience with the difficulties that arise when transitioning designs to manufacturing, there is little perceived need for manufacturing involvement until preliminary designs and

structure are defined. However, there are many factors to consider for Manufacturing Readiness. Many of these factors can be assessed early in the design process and these assessments can highlight latent deficiencies at these early design stages. Factors to be considered in the MRL Assessment are shown in Table 1.

Table 1 - Mapping of MRL Threads to AS6500 & AS9100 Requirements (MRL Deskbook, 2022)

Technology and Industrial Base	Requires an analysis of the capability of the National Technology and Industrial Base (NTIB) to support the design, development, production, operation, uninterrupted maintenance support of the system and eventual disposal (environmental impacts).
Design:	Requires an understanding of the producibility, maturity, and stability of the evolving system design, identification, and control of Key Characteristics, and any related impact on manufacturing readiness.
Cost and Funding	Requires an analysis of the adequacy of funding to achieve target manufacturing maturity levels. Examines the risks associated with reaching manufacturing cost targets.
Materials	Requires an analysis of the risks associated with materials (including basic/raw materials, components, semi-finished parts, and subassemblies).
Process Capability and Control	Requires an analysis of the risks that the manufacturing processes are able to reflect the design intent (repeatability and affordability) of key characteristics.
Quality	Requires an analysis of the risks and management efforts to control quality, and foster continuous improvement.
Manufacturing Workforce (Engineering and Production):	Requires an assessment of the required skills, availability, and number of personnel to support the manufacturing effort.
Facilities	Requires an analysis of the capabilities and capacity of key manufacturing facilities (prime, subcontractor, supplier, vendor, and maintenance/repair).
Manufacturing Management and availability	Requires an analysis of the orchestration of all elements needed to translate the design into an integrated and fielded system (meeting Program goals for affordability

Manufacturing Maturity Assessments (MMA) are used to evaluate and address all these threads early in product development with subject matter experts and individuals familiar with a business's Operations, Supply Chain, Facilities and Capital Resource Plans or Allocations to fully and accurately assess the MRL. However, most program or project teams may not have full time resources available from within these functions, particularly during early development phases.

In addition, because of an inconsistent engagement with Manufacturing and Operations functions, the Transition to Production interface is sometimes limited in size and process, thus resulting in processes which are characterized as "throwing it over the wall" transitions from Engineering to Production once the design has been completed and qualified. The desired state is to have a common practice process across the enterprise responsible for design and production of products to provide proper resource utilization and timely product deliveries.

The broad arrows in Figure 2 represent the "throw it over the wall" approach, where the Design Engineering organization has participants on many different Integrated Product Teams (IPT) that complete their projects independently from each other and independent of much Manufacturing Operations and Supply Chain involvement. The space between the arrows represents the Transition to Production engagement time and interface.

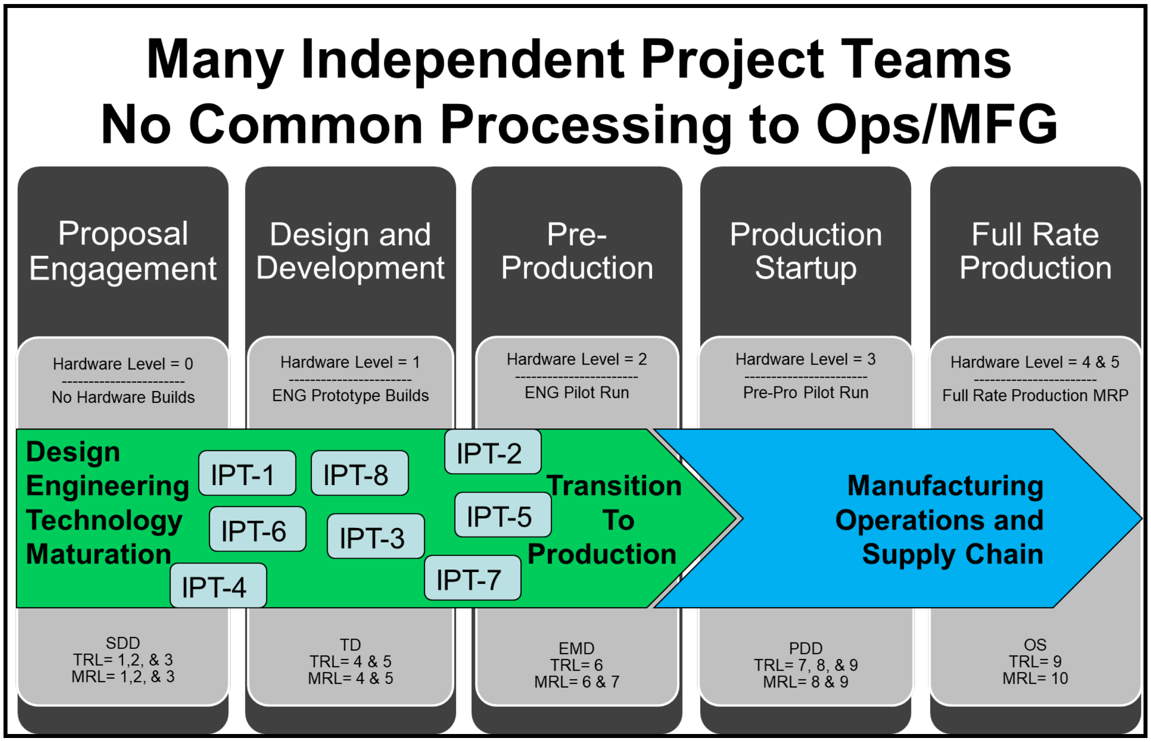


Figure 2 - Current Engineering Build Organization/Culture

Countermeasure Implementation

The final deficiency which arises from the application of TRLs and MRLs is the inability to develop and implement countermeasures or strategies during development to stay within cost, schedule, and requirement limitations. Because the manufacturing operations and supply chain functions within many organizations have their own metrics and strategic goals, one or more of their goals may not align with a specific goal or strategy required by the Integrated Product Team (e.g., facilities and capital equipment changes or funding are generally on a separate planning schedule with many other stakeholders beyond the project team). The MRL assessment does not evaluate and assure the goals of each function are aligned. Perhaps, if such an assessment were

developed, such goal alignment might improve communication and processes across the functional areas necessary to bring a product to deployment. Because some countermeasures will require a response which integrates actions across manufacturing and supply chain functions, it is not practical for individual project teams to implement countermeasures or to be responsible for achieving the appropriate MRL. It has also been observed that many organizations do not include a single organization with ownership of the actions required to mature manufacturing readiness for all projects. There should be a balance of resource assignments at the appropriate time for each project in relation to all others. There are resource constraints that the DoD Industrial Base or individual companies within it must deal with as part of their overall business model.

The incorporation of manufacturing processes into the Model Based System Engineering approach to evaluate design and systems solutions digitally prior to actual build and production of hardware requires key attributes and parameters to be established for use in those models. Establishment of these key parameters should be done by the key stakeholders responsible to the performance of those items as they affect an entire business operation. Typically, for a manufacturing center this would include productivity for labor, as well as material costs. Capital equipment utilization and return on investment of such equipment is also important. Test yields, rework costs, scrap are typical Cost of Poor-Quality metrics that are important and often a result of the design or manufacturing readiness level of the item being produced. To have an effective model, there needs to be not only a desired goal established for the key characteristics, but also a

source for the actual performance data that can be used to compare against the requirements established.

Problem Statement

Understandably, there are many resources needed to develop technology readiness with systems, software, and hardware engineering efforts to assure designs are able to meet requirements; however, resources focused on manufacturing readiness during early planning stages are limited. The program manager has a significant decision to make regarding manufacturing. They can invest in manufacturing readiness in a technology development project, ensuring that the design will be manufacturable but risking expenditure of resources on manufacturing analyses for components that may never be manufactured due to other design changes or cancellations. Alternately, they can delay the investment in manufacturing readiness until closer to the point of transition, assuming the risk that the design may be difficult to manufacture, increasing program costs, decreasing quality, and risking production delays. This approach may save the investment which might be made assessing the manufacturability of components that will never be produced. As the cost risks associated with early MRL assessment occur earlier in the process and are easier to identify during these stages, it is reasonable that investments in MRL assessments are commonly delayed until near the transition point. A program manager's decision regarding this tradeoff imposes significant risks within many programs. Thus, there is a need to redesign this process in a way that reduces the consequence of this decision.

Research Objectives

One potential approach to this problem is to not rely on assessments alone, but rather incorporate self-assessment directly in the project development process as work is being done. System Engineering leads and Program Managers are keenly focused on tracking technical requirements that are flowed down from the customer or higher-level system to assure they are met or properly incorporated in their subsystems requirements during the earlier development phases. Thus, there is much less focus on the requirements that may impact manufacturing readiness.

Manufacturing centers that produce qualified products have established metrics to constantly assess the performance of their products and processes used to produce them to assure compliance and continuous improvement. This assures the best value for all stakeholders and the ability to meet deployment and delivery commitments. However, engineering development labs do not typically assess the processes used to produce products and thus do not produce data that could be used in MRL assessments. It may be possible to incorporate some manufacturing center metrics in early evaluations to enable insight into potential MRL issues early in the process. However, selection of appropriate metrics is required. This research has the goal of better understanding which factors or objective evidence is used to establish Manufacturing Readiness Levels; and then determine a potential process improvement to use during the project life-cycle that will result in accelerating the transition to production.

The research needs to address what information is necessary, as well as how to best identify and track information that would normally be gathered in an assessment as it is created or becomes available. The research should also help address the resources to employ for such information tracking, as well as how the information can be incorporated into the regular review and engagements within IPTs or functional and business reviews to assure the right stakeholders and decision-makers can affect Manufacturing Readiness Level maturity for the products and processes being developed.

Research Questions

This research addresses the following research questions:

1. What are some specific objective elements that can be monitored or tracked concerning specific attributes or characteristics that can provide a current MRL status assessment of an item for projects in the Engineering and Manufacturing Development (EMD) phase?

2. Where do organizations manage objective elements associated with MRL status which could serve as the system of record for status and values of the key attributes?

3. Can such attributes be accessed via an on-demand query into a Model Based System Engineering tool to determine an MRL value for any component/part, sub-assembly or sub-system in a product or system?

4. What a notional process, involving MRL assessments early, would look like and how can that be used to inform production related decisions, with potential impact years in the future?

Research Methodology

This researcher's desire is to examine and evaluate the concepts, methods, and tools related to planning, organizing, leading, and controlling resources and processes in a technology-focused organization. Then, apply and evaluate the principles of organizational behavior related to managing people-centric processes in a technology-focused organization. Accelerating transition to production by manufacturing readiness focus during development is the topic of this research proposal, which has been a theme pursued as a professional objective and given more thought as part of the overall studies at the Air Force Institute of Technology (AFIT) Graduate School.

This research is intended to synthesize a working model from research and learning in Information Technology, Human Factors Engineering, and Model Based Systems Engineering at AFIT to benefit the DoD contractors and industrial base supporting the Air Force. The focus of this thesis is developing a model that (1) creates a common "process focused" approach to achieve efficiencies and predictability of processes, capabilities, and tools and (2) drives design influence based on manufacturing producibility in all phases of product development. It is hoped that such an approach could lead to reduced labor costs and cycle-times, enhanced factory utilization, improved personnel and product safety, reduced variation and rework, increased productivity and

process controls, improved manufacturing readiness levels, and accelerated transition from early product development to manufacturing.

The research for this thesis project will be done in four phases. These include a Literature review to discover existing development approaches and key elements associated with the transition to production process, construction of MBSE models of processes, organizations, and data elements relevant to the transition to production process, conducting discussions with individuals engaged in transition to production activities, and examination of any existing data set for vital information to determine MRL assessment.

The modeling process involves gathering data by examining the various activities and artifacts generated by those activities during the development project. The information is then organized into various graphical representations and tables in a manner in which they can be reviewed with colleagues and other stakeholders involved in the development process to discover what information may be missing such that it can be incorporated into the various diagrams and tables. The inputs are gathered throughout the process to form an overall solution model for review.

Once the overall model has been established to address the research questions, a further review with stakeholders is done to determine the usefulness of the model. The goal of this project is not to complete a working model, but rather to establish a conceptual level model which can be built out further with more development.

Assumptions and Limitations

The current research assumes that whatever design process is used or established, it will assure it meets the design and technical requirements of the product being developed. Even though the product performance of a design may vary regarding its overall capability, the manufacturing readiness level is achieved by faithfully reproducing the product design regardless of the design limitations. Therefore, if a design is qualified as successful with a given yield or variability in performance, the manufacturing process is fully matured when it can meet the full rate demand for the product with the given yield.

The research is also resource limited to the time frame of the program coursework, which limits the result to a conceptual model on how the MRL can be monitored with data generated from the development process and evaluated with appropriate information systems. Although there may be some proposed data structures or reporting methods, there will not be sufficient resources applied during the research project to build a working model that can be used to calculate a MRL value from real project data. Therefore, there is no calculations or data analysis included in the results of the research. If the model is found useful, subsequent research or development may be necessary to put the model into effect for a demonstrated capability.

Another limitation in this research is scope of activities and organizations being studied. The availability of multiple program teams across businesses outside of Raytheon is limited. Thus it will be assumed that observations based upon knowledge of

functions and activities in Raytheon will generalize to other environments. Raytheon works with multiple partners in cooperative projects across major suppliers, as well as working with multiple subcontractors, who support development of their subsystems as part of the Raytheon product offerings. So, although not perfectly representative of the whole industry, the Raytheon perspective of this study will provide a significant level of diversity. One other limitation is the researcher's personal bias which is derived from working transition to production process for commercial business for many years and their resulting prejudices toward some methods and processes which have had apparent success in similar environments. DoD development has some particular challenges that set it apart from the standard commercial practice. In additional, this researcher has spent more time on the receiving end of transitions into manufacturing than working and engaging in the design and development part of the process. Additional reviewers will be included, especially in the preparation of feedback and input questions, to limit bias.

Implications or Expected Contributions

The expected results of the research are to have the information gathered put into an effective model that will enable a continuous monitoring of MRL status and pending work packages to complete throughout the development life-cycle. It is expected with the added visibility and monitoring built into the MBSE approach, project teams will have an opportunity to see advancements in MRL levels when completing necessary tasks within the project. There will be a better ability to prioritize and accelerate transition to production for those critical programs that need to have a rapid operational deployment as needed for national security objectives and special mission objectives.

Preview

The Literature Review in Chapter II explores information regarding the Manufacturing Readiness Level Deskbook and associated Manufacturing Maturity Assessments along with previous research regarding the transition to production process. Chapter III explains the Model Based System Engineering (MBSE) method to be used to model the process with Chapter IV explaining the MBSE model development. Chapter V describes the MRL Item Assessment criteria with a description of the analyses processes. It also explains how the results of the modeling process methodology are used to answer the research questions in this chapter. In addition, Chapter V provides the conclusions and recommendations from the research of the thesis.

II. Literature Review

For the Literature Review, there were three principal areas of research that were included. These include the system engineering approach to the development process, which could include the manufacturing readiness of the product. The next area involved the current process used for manufacturing maturity assessments during the development and transition to manufacturing processes. The final area was application of Model Based System Engineering (MBSE) approaches to manufacturing process and associated maturity. Included in each section are some of the significant findings from the literature.

Overview of Manufacturing Readiness Levels

The Manufacturing Readiness Level (MRL) Deskbook reference is not a peer reviewed article but rather a publication by Department of Defense which was developed in collaboration with Industry and Academia. It is available at http://www.dodmrl.org/, which is a collaborative Industry, Academia and DoD website that provides the updated references and tools which comprise the MRL Body of Knowledge. It is included in this literature reference because it is the definitive reference for the term "Manufacturing Readiness Level (MRL)" as presented in the Deskbook. As a summary, it describes the overall life cycle process of product development as managed in the overall Defense Acquisition Industrial base. The manufacturing readiness is understood to be done in parallel with the Technical Readiness Level (TRL) of the product or system being developed. The MRL cannot advance to far ahead of the TRL, in that the technical requirements to be satisfied and qualified before full maturity can be achieved regarding

manufacturing readiness. TRL is rated on a scale of 1 at lowest level to 9 at the highest level of technical readiness. MRL is rated from 1 at the lowest to 10 at the highest being at Full Rate Production (FRP). It can be seen throughout the diagrams and process explained in the Deskbook that TRL and MRL need to be maturing together and closely aligned, because in order to do the qualifications need to reach operational readiness, the product evaluated must be representative of what will eventually be deployed into operation.

There are ten levels of MRL criteria that begin with pre-systems acquisition; progress through systems engineering reviews, acquisition decision points, and milestones; and culminate in production. See Table 4 in Appendix B for the full list. Each of these levels is associated with the evolution of system maturity (i.e. developmental state changes such as bread-board, brass-board, prototype, production configuration, LRIP, and FRP).

- MRLs 1-4: Criteria address manufacturing maturity and risks beginning with pre-systems acquisition (MRLs 1 to 3); continue through the selection of a solution (MRL 4).

- MRLs 5-6: Manufacturing maturation of the needed technologies through early prototypes of components or subsystems/systems, culminating in a preliminary design.

- MRL 7: The criteria continue by providing metrics for an increased capability to produce systems, subsystems, or components in a production representative environment leading to a critical design review.
- MRL 8: The next level of criteria encompass proving manufacturing process, procedure, and techniques on the designated “pilot line”.
- MRL 9: Once a decision is made to begin initial production (LRIP), the focus is on meeting both quality, throughput, and rate to enable transition to rate production (FRP).
- MRL 10: The final MRL measures aspects of lean practices and continuous improvement for systems in production.

The basic goal of all acquisition programs is to put required capability in the field in a timely manner with acceptable affordability and supportability. To be successful, the two key risk areas of immature product technologies and immature manufacturing capability must be managed effectively. Manufacturing readiness metrics in combination with technology readiness metrics can help acquisition program managers deal with these risks. Similarly, these metrics are important to technology development managers because, they can be used to achieve and convincingly demonstrate a level of readiness for technology transition that acquisition program managers will find credible. Understanding and mitigating these risks will greatly increase the probability of technology insertion for the technology development community and ultimately aid in improvements in cost, schedule, and performance for programs of record.

It is important to understand the System Development Process and how Manufacturing Processes and MRL Assessments fit into the System Development Process. Important to the viewpoint within this thesis, each component buy, build, procurement, or assembly, regardless of its maturity level, is an exercise of the manufacturing process. Therefore, there is data and information created during these processes and builds, regardless of when they occur within the development life-cycle.

System Engineering Methodology (“V” Model and Manufacturing Aspect)

The Systems Development Process begins with Architecture development. Activities conducted during this phase include activities necessary to achieve MRL 1 and 2 for the system under design. During this phase various materials and process are considered as available elements to solve the problems necessary to meet the stakeholder requirements. Information may be gathered concerning physical properties, processing methods, sources and costs for inclusion in a solution, known as the Material Solution Analysis (MSA) Phase shown in Figure 3 (Engineering of Defense Systems Guidebook, 2022). At this point a key decision involves how much of the solution will be creating something new versus repurposing or adapting existing, somewhat mature, technology. Even at this early level of the development process, the major components or subsystems contemplated have a mixture of MRL levels. During an analysis of alternatives for a design approach, considering the MRL of the alternatives could help determine the workload risk to plan for each alternative within the following phases. However, to understand MRL for each alternative it will be necessary to find data or previous assessments of such components or subsystems under consideration.

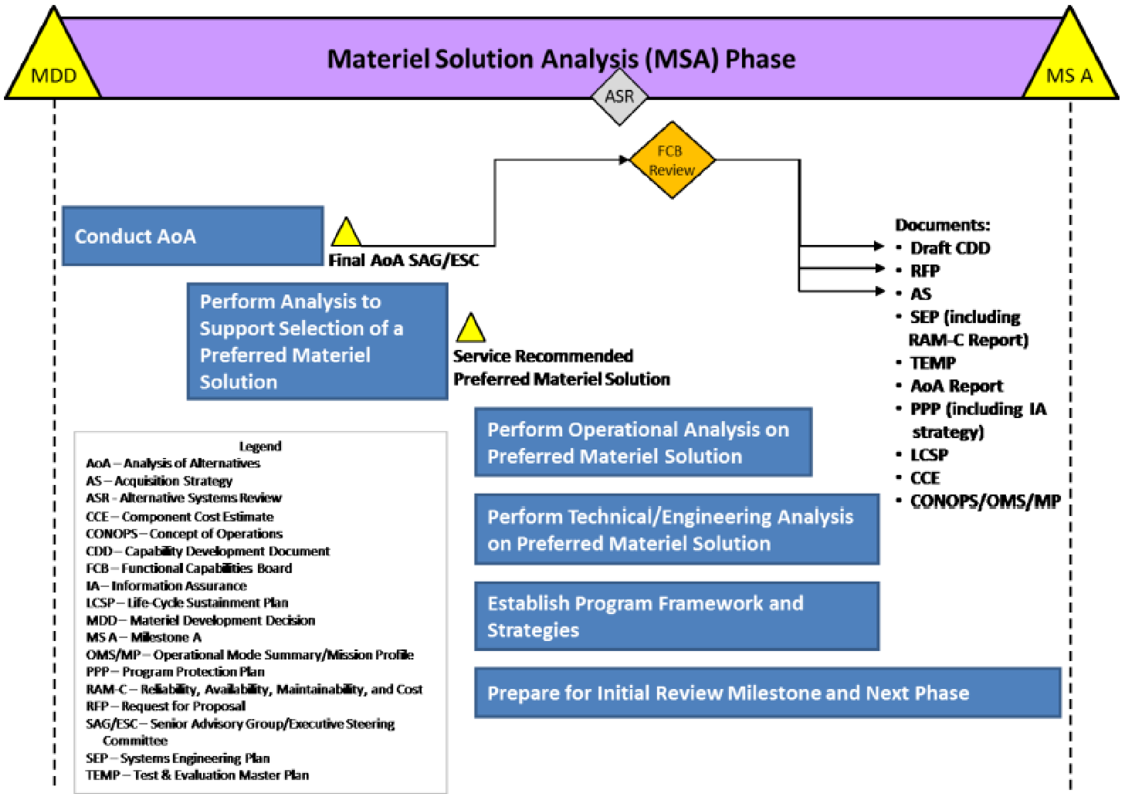


Figure 3 - Activities in Materiel Solution Analysis Phase (DAG, 2018)

Once the System Architecture has been designed, the next phase is Subsystem design. Besides the analysis in Figure 3, it is good to consider some of the activities of this phase as depicted in Figure 4. The function allocation that takes place in this phase defines much of the criteria that will be used for verification of parts and subsystems to be included in the design. As such, it is the right time to determine test and evaluation methods and how to assess the quality and critical characteristics that would affect the overall system performance and success. In this phase, tradeoffs are evaluated and alternatives are considered. With the completion of this phase, one should not only be able to understand if the design characteristics from a system performance perspective meet the stakeholder requirements, but also whether the method for acquiring or

producing the parts or subsystems are consistent with the stakeholder requirements before moving to the next phase. Therefore, the MRL assessment criteria which relate to stakeholder requirements, such as cost and volume, would be good to understand and apply within this phase.

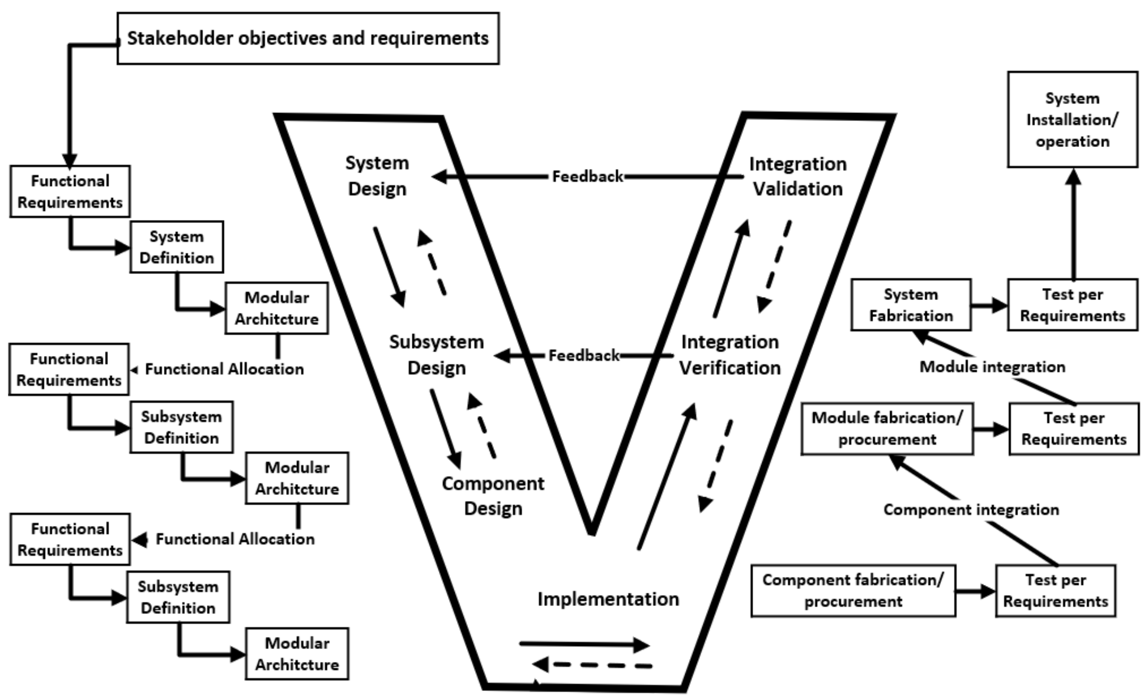


Figure 4 - "V" Model Process Includes Feedback from Integration & Test

Revisiting Figure 4, we see the last phase of the development is the Synthesis: Physical integration phase. Figure 5 represents this phase beginning at the bottom of the "V" where Build/Code Components occur. This phase includes the travel back up the right side of the "V" for the verification that each component or subsystem meets its requirements and, after integration, supports the overall system being validated as able to accomplish its mission from the user or customer perspective.

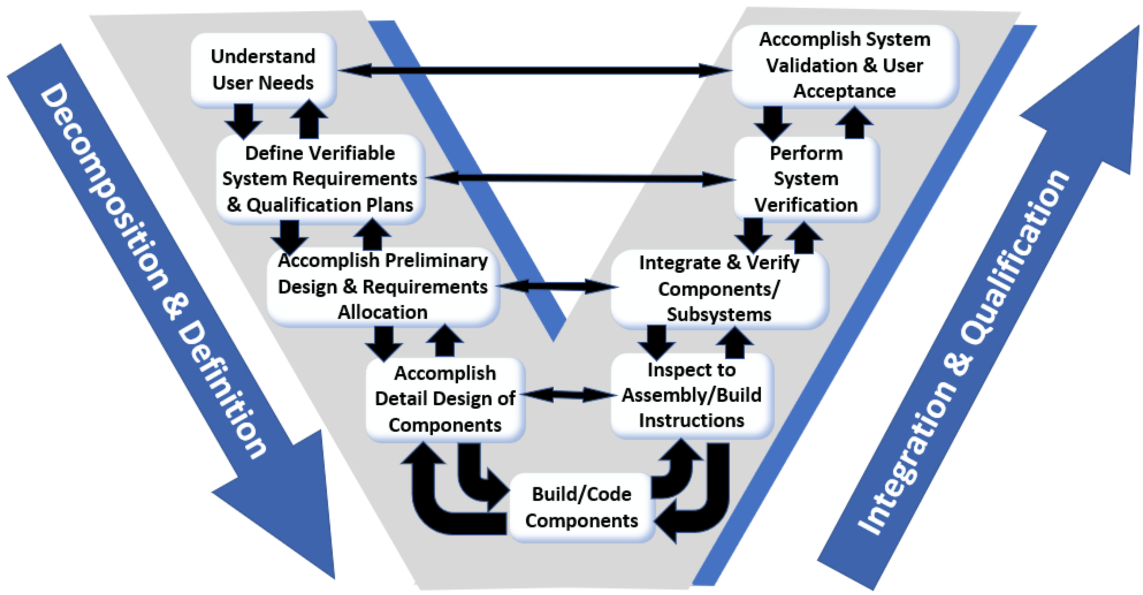


Figure 5 - Different Perspective of "V" Model with "Build" at the Fulcrum

One other perspective of the Systems Engineering process model, depicted in Figure 6, shows that multiple disciplines are involved in the definition and evaluation of the requirements. For example, Human Factors are shown as a necessary consideration and inputs into the requirements development, not only at the Customer or system operator level but also at the components and subsystems. It is important to consider Human Factors in the Manufacturing Readiness from several perspectives. Some of these include physical constraints and limitations of the workers involved in the assembly and integration processes, as well as other required skills concerning training and experience requirements of the workforce required. In addition, there are Human interactions with equipment used for testing or processing the assembly/integration that have interactions with the overall manufacturing methods. The bottom of Figure 6 shows an indicated process step depicted as multidisciplinary optimization. Certainly, a key set of disciplines

for the build stage are supply chain and manufacturing operations. Thus, it is important to assure their criteria and assessment factors are included in trade off decisions which occur within this multidisciplinary optimization. Manufacturing and test engineers' criteria and assessment factors are also included as part of manufacturing operations.

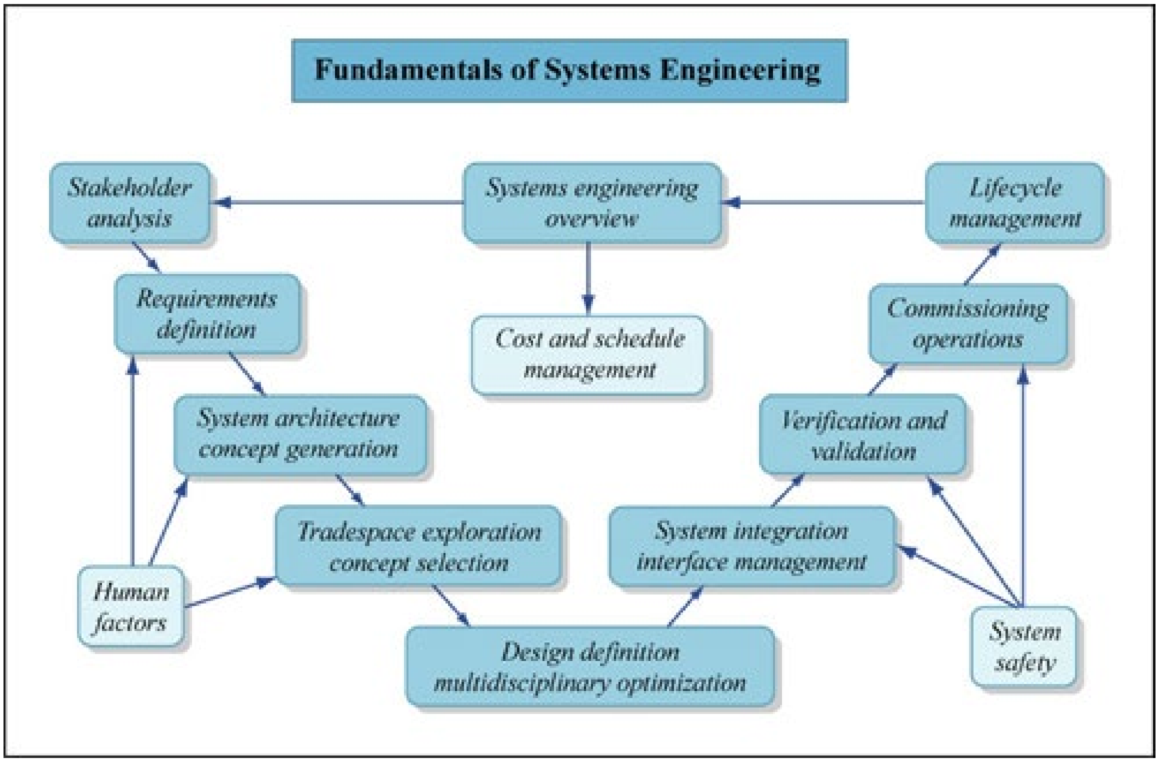


Figure 6 - Another Perspective of the "V" Model (MIT OpenCourseWare)

Research by Ross has described a method of combining the TRL, MRL, and IRL ratings into an overall System Readiness Level (SRL) metric to provide guidance to decision makers on the development stages of a project (Ross, 2016). One of the essential management practice recommendations is to achieve the overall movement in the maturity of a product or system, there must be focus and management of all the components that make it up. This paper indicates the need to have good assessments in all

the various areas of the development, including MRL, to make the appropriate resource decisions that will advance the project in a timely manner. In some cases, this means assuring that the technology advancement is not moving to far beyond the development of the associated manufacturing readiness. Examples of undesirable outcomes resulting from misalignments are provided, including how motorcycles were first designed with fixed foot-pegs. Only after some spectacular spin out wrecks was the design changed to folding foot-pegs. He also references how the F-35 development advanced ahead of its interfaces and component manufacturing to delay its operational capability (Bender, 2015).

Another example of how the importance of the process used to manage the technical development should include the use of MRL assessment is provided in an article by Treamaine (Tremaine, 2009). This article discusses a design development methodology used in Defense Acquisition which includes the combination of two popular methodologies to give improved results. Specifically, it combines the System Engineering (SE) process model for problem-solving to a key process model of Lean Six Sigma (LSS). SE uses a process that first assesses the deficiency with a requirements analysis, then logically and iteratively decomposes those requirements into design functions. Subsequently the overall design is synthesized with trade studies within the design envelope. Afterwards, it is built, tested, and fielded with analysis and controls along the way. The SE Technical Management Processes are used to manage evaluate the progress of transforming concepts into reality with checks such as assuring the TRL and MRL are at the target levels established for the current life cycle state.

LSS is not focused on system engineering; however, it does focus on a drive to improve speed, quality, and cost associated with a product and thus influence the design decisions made what addressing problems. A fundamental problem resolution process in LSS is Define, Measure, Analyze, Improve, Control (DMAIC). The article discusses the similarities in these processes; however, it also indicates that the combination of the two is more powerful that either by itself. LSS and DMAIC are seen to be more innovative and able to enhance the traditional SE processes. Tremaine states: "*In fact, process is inextricably linked to just about everything that SE and LSS do—reinforcing the underlying common process bond they both share. Oddly enough, process is not the enemy of innovation that some might think. Instead, it is the foundation for innovation since it more critically describes what should stay and what could go.*"

Another approach is the Product Development Business Process (Holmes and Campbell, 2004). This approach uses gating phases and was originally proposed as the Product Development Process during the 1980's and 1990's; and updated in 2002 and discussed as part of MIT Center for Innovation in Product Development conference. This process seeks to reduce barriers of initiation and launch stages of the product development process by implementing a more continuous process through transitioning to an end-to-end process. A key factor in this approach is the integration of the business requirements into the product design and manufacturing process with the end-to-end goals concerning investments and revenues. Manufacturing Readiness Levels, that may be seen as a transition to launch activity, would be considered a barrier. In this approach MRLs measured continuously from the beginning of the strategic front end of the project.

Because there is a goal for business case achievement that includes Quality Improvement, Cost Reduction, and Contracting; performance goals outputs provide feedback into the root causes and improvement initiatives during the earlier development stages to influence the Senior Management Team all through the development life cycle. This research concludes with three vectors to improvement of the product development process by, 1. Implementing an end-to-end development process from the front end through the field operations; 2. Implementing business objectives more effectively into the process; and 3. Establishing a closed loop system that sustains business performance improvement.

Mortlock discusses another approach to streamlining product acquisition (Mortlock, 2020), referred to as Incremental Development (ID) plans can get new capabilities to the warfighter sooner than a single step development approach. In a single step approach the product must go through all the gates and phases in a slow and complete assessment on the way to full technology readiness. With an incremental development approach, the capabilities are delivered into the field quickly, even if not yet the full capability planned. The faster delivered technology improves capability over the current situation. It can effectively deliver the most benefit at the lowest cost, while the further, more costly capability comes later, which could ultimately be decided not to be needed.

There are key enablers for this approach that include Time Phased Requirements and a Modular Open Systems Approach (MOSA) to facilitate later insertion of technology at subsequent points; with funding, testing and evaluations staged

appropriately. This approach is compared Evolutionary Acquisition (EA) that builds capability in blocks with proven and available technology. This research makes a point that the ID and EA approaches provide a more rapid deployment of the improved capability with lower risks as the highest risk technology is delivered successfully with appropriate cost, schedule and performance once it has achieved.

It is supply chain disciplines that take on a large role during the Build or System Construction phase. In Figure 7, there are two perspectives one can take. A first perspective is that during the overall development process, there are multiple “builds” that occur. The early build may be a digital model as would be developed using tools and processes of Model Based System Engineering, where assessments can be made prior to hardware or software fabrication or coding. Then there are several other builds, each with a higher Technical and Manufacturing maturity. The diagram shows relative TRL/MRL levels for each of these builds. The second perspective is the development effort and discipline involvement shifts from the System and Design Engineers to the Manufacturing and Test Engineers as well as the Operations and Supply Chain disciplines as the program progresses. As this diagram shows, there is participation of the multiple disciplines in the development process; this process should possess the ability to capture the assessments made during the early build events which informs the further work which is necessary to achieve the transition to production and higher the MRLs desired for the fielding of the system.

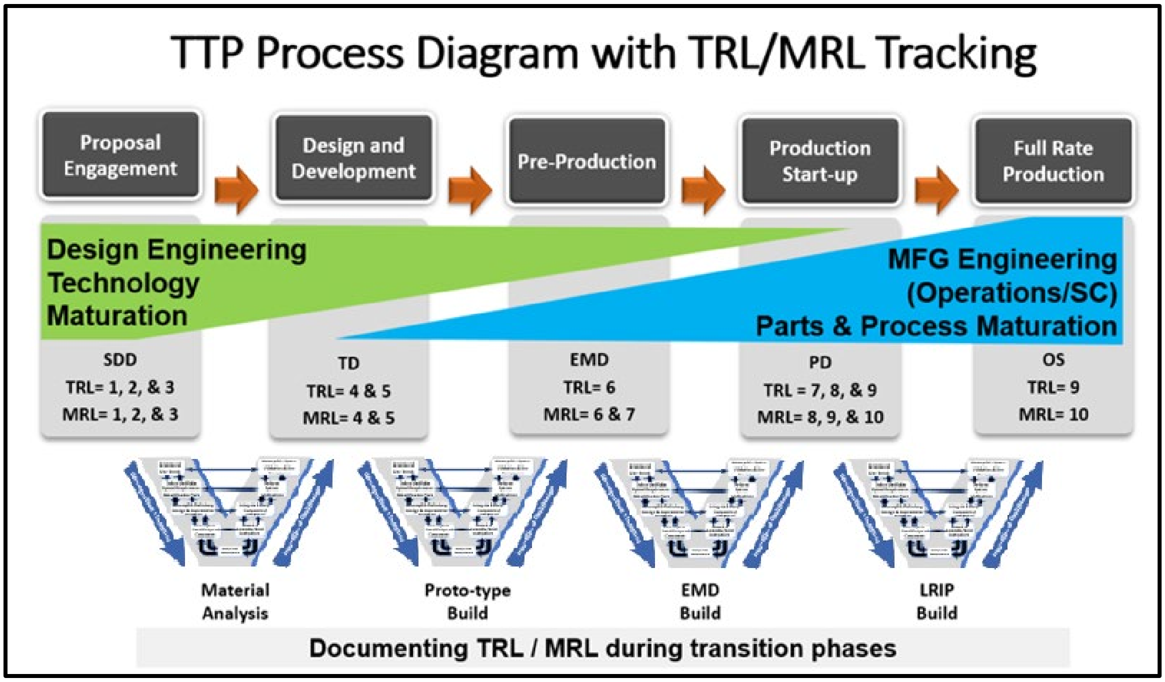


Figure 7 - Multiple "V" Builds & Assessments

The arrows from Figure 2 have now been replaced by ramps in Figure 7. If the arrows and ramps were to be considered as three-dimensional objects, then when those objects are joined to together, the surface area of where they touch would represent the interaction and interface between the two groups. Since information must transfer between the two groups during the Transition to Production event, the process approach with the ramps indicates there is a larger surface of Transition to Production occurring early in the development process. Transition begins with the interaction of these two functional discipline groups. It should start from the first build of any item conceptually, even if only in models or prototypes.

Explore Manufacturing Readiness Level Assessment Criteria

It is also important to examine the objective evidence and attributes used to conduct MRL Assessments. In this section, assessment tools and case studies which provide examples of the items which are tracked to be included in MRL assessments are discussed. This section forms the basis for determining the most valuable information to track, as well as the types of attributes or characteristics which seem to be missing.

It is found that the MRL Deskbook criteria have been converted into survey tools that are used to assess manufacturers of a product or subcomponent based on the nine threads that are evaluated and that are considered to impose potential risks to meeting manufacturing goals if not addressed. Versions of the tools used evolve and the most current one is found at the website for DoD Manufacturing Readiness Levels (http://dodmrl.com/). One such version of the assessment tool was configured to provide a set of questions to be answered when assessing each of the nine threads or twenty-one sub-threads. This assessment tool includes over 450 questions that could be asked as the development progresses through the phases. As part of answering the questions in the assessment tool, the one being assessed would supply artifacts or objective evidence to support the MRL rating or compliance with what is expected for that particular sub-thread to be at the assessment level. Anywhere a deficiency is found for the expected or desired level, an action plan is developed to mitigate the risk that area will have on the transition to production.

An article entitled "*How to conduct prospective life cycle assessment for emerging technologies?"* explains the challenges of conducting life cycle assessments (LCA) for emerging technologies (Thonemann, Schulte, & Maga, 2020). It provides an overview of the process and methodologies used. There is a recommendation that both TRL and MRL should be used as part of the overall LCA methodology. It indicates that more study is needed to reduce uncertainty and make more reliable LCA for use in evaluation of maturity in development. Overall, the study reviews multiple technology developments and discusses how all the information gathered was analyzed to determine how well it could be leveraged or scaled across different applications or projects. It looks at how a process may move from a conventional process technology in manufacturing to an emerging technology process with an appropriate scale. It ends up with multiple methods that could be applied; however, it states that for better transparency, the TRL and MRL of the technology observed should be known and stated. This implies that it is not always known or stated. It appeals for more information provided on MRL and how it is an important factor to understand in relation to life cycle analysis and other decisions to be made regarding technology investments. It does not provide any examples of MRL assessments though.

An article entitled *"Assessing transition readiness for radical innovation"* focuses on assessment tools and evaluation of the additional uncertainties that need to be addressed to reach the full maturity and readiness (O'Connor, Hendricks, & Rice (2002).

In an article entitled "*Achieving manufacturing readiness for 6-inch HgCdTe on silicon"* (Paden and others, 2010) provides a very detailed example of how MRL was

matured during the development of Large-Format focal-plane arrays (FPA) with some objective evidence used to increment the MRL levels. This is one of the few examples in the literature with some specific manufacturing readiness challenges being addressed beyond the technical readiness.

An article entitled *"Integrating immature systems and program schedule growth"* reviews the overall development process and how it was measured and assessed over its life cycle (Kamp, 2019). It explains some of the delays and cost growths that can occur. It may be possible to use this article to determine how similar delays and cost growth can be avoided in other development programs.

The article *"Analysis of military construction COST GROWTH in USAF MAJOR DEFENSE ACQUISITION PROGRAMS* covers cost growth experienced in construction projects (Angell, White, Ritschel, & Thal, 2020). The overall evaluation includes not only the development process, but the bidding process as well. This article points out that many development projects can overlook the work and risks involved in preparing for manufacturing readiness in addition to maturing the product or system technically. The information and approaches from this article can be synthesized into an overall research strategy to determine approaches to address cost growth in acquisition programs. The essential foundation of this article is a relationship of cost growth over time with the number of reporting periods involved with the program. It implies that if even the same amount of work is expended during a project; a more rapid transition to production can result in overall cost savings due to the shorter period of performance.

No examples were found, where a predetermined set of criteria was established at the beginning of a development project to permit working the plan in parallel with the design activities during the development phase. The most important part of this review was to understand that there are many aspects to consider for manufacturing readiness. Even though the MRL Deskbook provides descriptions of the threads for various levels of maturity, it is left very open ended to be able to encompass a broad set of industries and technologies that are included in projects.

From this review, it was determined that any modeling or additional information gathering should explore the entire scope of the multiple threads involved with manufacturing readiness. There are no one size fits all type of metrics or criteria to be used across the various industries. However, certain metrics or criteria may be of greater impact and utility to each business or industry.

MBSE utilization for Modeling the Manufacturing Process

Multiple examples were sought to examine MBSE models and how such aspects of user and machine interfaces are included in the modeling. Just as there has been research into Human Factors modeling from the operations perspective in deployment of a system at that point of its life-cycle, the same approach can be used for modeling the assembly operator and test technician interfaces with the components and subassemblies to build and test the product during the manufacturing process (Watson et al, 2017). Transition to Production activities will include the planning and monitoring of the tasks

needed to reach the desired performance of the product and the manufacturing processes during the development life-cycle.

Bock and Odell (2017) also published a useful model that demonstrates the use of MBSE to model a manufacturing process. This model can be used to manage or predict an output time or schedule performance for work requested based on the limited resources in a factory (Bock and Odell, 2017). It demonstrates that having certain attributes organized in a model can help predict performance and duration or capacity and rate at which manufacturing can occur versus the desire demand. The resource limitations in the model with their associated objects and attributes could be reconfigured or copied and converted to model other resource limitations or aspects of a product development process and the various threads to be assessed for manufacturing readiness.

Chapter 5 of the Defense Acquisition Guidebook (DAG) (2018) "addresses Manpower Planning and Human Systems Integration (HSI) in the Defense Acquisition process. It provides guidance for including a total-systems approach; documenting manpower, personnel and training elements; and use of program manager tools that incorporate HSI considerations in the acquisition process appropriately. It also explains how HSI minimizes total ownership costs over the life cycle of a program

In Extending System Readiness Levels to Assess and Communicate Human Readiness (Miller, Thomas, & Rusnock, 2016), the authors demonstrated how to meld the Human Factor evaluation into the current known system of Technology Readiness Level (TRL) and Integration Readiness Level (IRL). This enables providing a method to have

measurable results that can be actionable by the Program Management and leadership team with relatable factors. However, most importantly, the systems engineers and team doing the design development work must get such requirements understood early in the System Requirements for the overall development of systems to address risk. The opinion of the author is that this is an important step toward addressing the modeling and analysis determined needed early in the process. This modeling helps get the requirements into an actionable form in the system engineer’s language. Additional research has been found to further support this approach and advancing this practice.

Expanding MBSE to Incorporate Human Systems Integration Modelling include a diagram that helps visualize the integration of HSI into the V model in the development process (Rountree and Thomas, 2021). In the graphic there is a double headed arrow between each side of the V at the various decomposition points from System Level down through the Part Level. These arrows represent a key communication of requirements and associated measurement criteria that must be established as part of the documented configuration management process. That defines the items at those levels as well as establishes the verification and validation process of those requirements. This is where critical evaluations are needed to determine whether or not each item is effective and providing its appropriate contribution to the overall system objectives.

Besides flowing down requirements for consideration by systems engineers and other engineering disciplines decomposing them and determining the elements needed for the solution, Model Based System Engineering (MBSE) enables dynamically modeling each of the actors in the overall system. Expanding MBSE to Incorporate Human

Systems Integration Modelling (Rountree and Thomas, 2021) explores the potential creation of a method to integrate HSI modelling and metrics into current systems engineering lifecycle modelling practices with the use of Model-Based System Engineering (MBSE). It finds that Human Factors Integration (HSI) is generally limited to the interactions via the model as actors in use cases. Engaging early in the process prior to architecture being completed better enables influence to design at a lower cost point than when addressing problems later in development due to such requirements not being considered.

Technical Readiness Assessments (TRA) are expected at each Milestone; however, to understand how advanced the technical readiness has matured, there should be consideration to where the program is with its Manufacturing Readiness Level. Often, programs have these as "follow on" activities and optional for consideration, once the technical solution is developed. They need to be completed as part of the development in order to mature the design. A very important factor in the design for producibility is to have a definition of Manufacturing Workflow and Assembly Operations established. This enables understanding the Manpower Requirements and Human Factors associated with those roles. In addition, it is very important to have a Definition of Test Process Flow and Test Operations established early as well.

It is important to document not only the requirement, but also the measurement method to be used to verify or validate that performance at the level needed. In some cases, the measurement system may need to be developed as well. This is especially important to incorporate into the modeling of not only the product and its performance

requirements, but also the modeling of the associated test and/or inspections. Those are done as part of the verification and validation phases as well as the production of the items in the manufacturing process. All Testing Requirements should be defined and documented in both the configuration management system as well as modeled in an MBSE tool, including:

- Workmanship Screening Tests (including Inspections)
- Design Verification Tests (including Qualification Tests)
- Acceptance Test Procedures and Special Test Equipment

With automation, there will be different skills levels and training needs. (Charalambous, Fletcher, & Webb ,2017) The development of a Human Factors Readiness Level tool for implementing industrial human-robot collaboration, an approach was addressed on how to get the workforce to accept use of robotics into the manufacturing process. It provides a schematic for a Human Factors Readiness Tool to aid engagement and introduction of robotics into a workforce. It is focused on the management support and stakeholder involvement.

For Full Rate Production manufacturing modeling, it is necessary to determine the expected test times for executing each screening and ATP included in the overall manufacturing process. These do not only determine processing time; they are critical in determining the overall facilities and capital equipment requirements to meet the volume and rate of production expected. Human Performance Models as well as Learning Levels

are important factors to determine what is needed to meet the rates for future production lots.

The article "ACQUISITION CHALLENGE: The Importance of INCOMPRESSIBILITY in Comparing Learning Curve Models, shows how learning curve models can be affected by how much automation is included in the system and the overall human interaction by the operator (Moore, Elshaw, Badiru, & Ritschel, 2015). Another point highlighted was, "While a vast collection of theory and studies exists relating to learning curves, very little attention has been given to the performance degradation due to the impact of forgetting (Badiru, Elshaw, & Everly, 2013)." During development and overall acquisition process, there can be long times between builds from an EMD phase and LRIP or full rate production. With personnel reassignments and turnover, learning cannot be assumed to reduce rates as may be expected with uninterrupted continuous build processes. The consideration of automation and machine activity versus touch labor is a key aspect of Acceptance Test Procedures that are developed for transition into Production. This is also an important consideration of that should be considered, especially in the software and firmware of a product design. It is a general practice to include as much Built-In Tests (BIT) as possible; however, this often requires some interface to others for either test automation or data to be provided to others in the system.

Informing System Design Using Human Performance Modeling *(*Watson, Rusnock, Miller, & Colombi, 2017) further show how to model interactions and effects

of automation. It also shows how SysML is used to create a System Block definition diagram for human factors.

To develop Test Procedures, it is important to determine which tests must be included in Acceptance Test Procedures (ATP) and which values should be 100% to assure functionality and no workmanship issues. Which test data items should be recorded? How often should test requirements not included in the ATP be audited or evaluated by engineering? How will data be processed and kept as records? These questions must be answered through analysis, and modeling can help; however, there is an iterative process required to start with some assumptions and then validate through the modeling process whether or not the test strategy started with is effective.

Once the test strategy is defined along with the overall workflow, it is important to determine what Human to Equipment Interfaces are needed. Part of the strategy will include determining the mount of automation required. Automation could be selected because of throughput capacity is needed or to reduce the human interface needed as part of the test process.

Modeling the test process and evaluating the results can also help determine if test or assembly yields indicate the design is at the maturity level desired. There are often multiple tradeoffs to consider in the design, which of course must pass the technical requirements; however, as the development proceeds there should be data gathered studies made to determine overall effectiveness of not only technical performance, but also whether or not the Human Factors and other factors have been addressed. (Madni

and Orellana, 2018). Extending model-based systems engineering to address human-systems integration considerations in the system life cycle demonstrate that it is possible to perform the analysis in MBSE methods. This enables improvement of the design to address human factors, such that overall effectiveness of the solution is improved. The case study builds upon previous modeling efforts and shows that after modeling the human interfaces of the system, automation could be targeted to where it would be most beneficial and address some of the original design effectiveness issues.

Summary

Information from the Literature Review illustrates connections between design engineering and manufacturing, the utility and effort necessary when performing assessments of Manufacturing Readiness, and models relating to manufacturing process. However, what is perceived to be missing from the literature are examples or guidelines for processes to transition products to manufacturing. Any preparation or work related to preparing for transition to production is vague and while periodic MRA assessments may be useful as they are conducted near a phase milestone, they often reveal deficiencies too late to correct without project slips.

The information gathered in the Literature review help form a basis to develop a model on the type of information needed for the transition to production process. The further research and methodology used will build upon this information.

III. Methodology

This chapter describes the research methodology used to answer the research questions. Therefore, the methodology used must not only explore the objective evidence needed to determine the MRL of a product or item during its development, but also the process and people involved in producing the related objects and information. Besides producing the objects and information, the methodology should determine an answer addressing the management of the information to dynamically assess current MRL values of each part of the system structure and inform the decisions made that affect the appropriate maturity level desired at any point in time. The methodology should help answer if management of the MRL during development could aid a team in accelerating the transition to production.

Overview of Research Methodology

To answer the research questions, the methodology uses a Model Based System Engineering (MBSE) approach to determine the overall development process and determine the appropriate objects and attributes on those objects that can be used to understand the manufacturing maturity and readiness level for production along the overall development cycle. The Cameo Enterprise Architecture version 19.0 tool from No Magic, Inc. was used for the modeling work using the SysML style diagrams available in the System Engineering Perspective for the environment set up. Figure 8 shows some examples of the diagrams and layers of architecture possible with this MBSE tool. It also implies the iterative nature of MBSE.

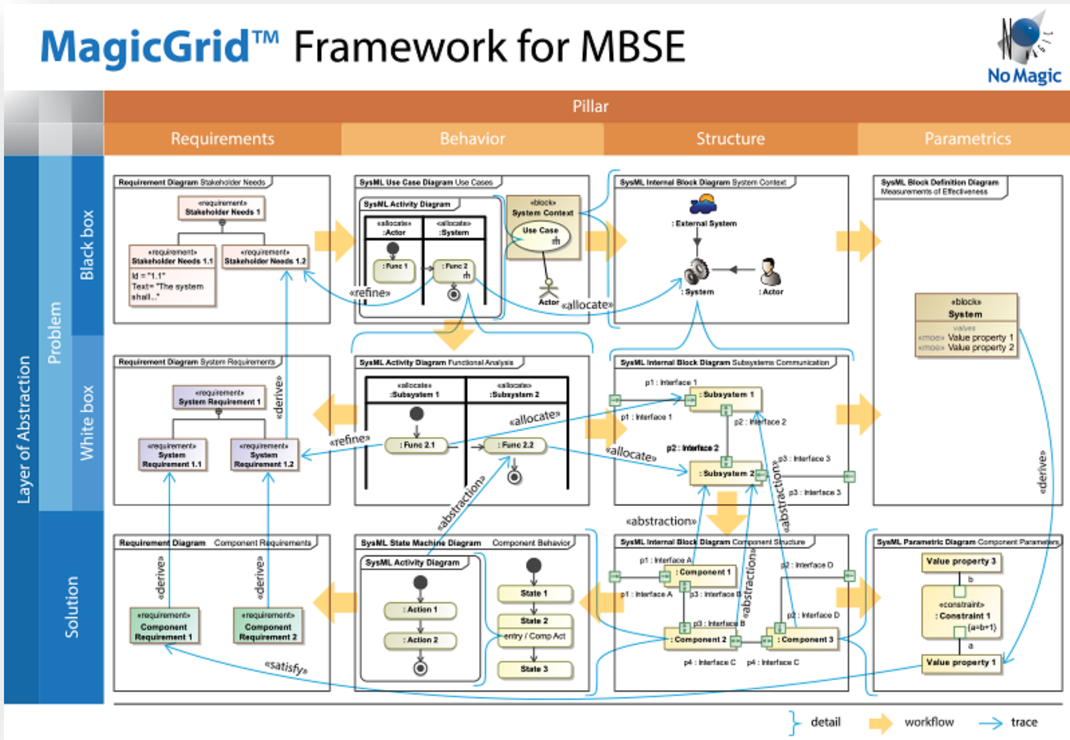


Figure 8 - Magic Grid (https://www.nomagic.com/support/quick-reference-guides)

The model published as Ontological Behavior Modeling by Bock and Odell (2017) mentioned in Chapter II inspired the development of the current model to examine the problem. Their model demonstrated the use of MBSE to model a manufacturing process and manage or predict an output time or schedule performance for work requested based on the limited resources in a factory. It uses a few simple process steps in manufacturing such as paint and dry to complete a request to change the color of an item. In the current research, a model is constructed not to understand the manufacturing process but the process necessary to transition a product design to manufacturing.

The scope of the model developed for this research makes multiple assumptions. First it is assumed that the design project's technical and operational requirements have already been determined. Therefore, the design can be started with the Technical Requirements necessary to meet the System Requirements or Use Case it was intended to accomplish. Additionally, the desired final production level deliveries of the project or program have been specified through a Statement of Work (SOW) to the developer. It is also assumed that the requirements associated with manufacturing and delivering the quantity of product within a specified time, while meeting the cost constraints and quality requirements have been specified in the SOW. Therefore, the MRL can be considered in relationship to the existing requirements. It is assumed that the process starts when the design work begins and ends when all product items have been delivered at the rate needed within the cost and quality requirements.

The SysML diagrams used in the modeling steps were as follows:

Use Case (UC) Diagrams

Use Case (UC) diagrams are used to model the overall "V" development process described in the literature review earlier. This includes an expansion of activities on the V model to capture the roles of the Manufacturing and Test Engineers as they complete their required deliverables. It also adds the role of an Operations Manager who develops the overall Manufacturing Plan from the Requirements found in the SOW as well as the products produced by the Manufacturing and Test Engineers.

Block Definition Diagrams (BDDs)

Block Definition Diagrams (BDDs) are used to define the elements associated with the Manufacturing Plan as well as the roles in the Organization that are necessary to produce the key objects of the development process that help assess manufacturing maturity and MRL. A BDD is also used to model attribute values which are required in an information system to facilitate the required MRL assessments.

Activity (act) Diagrams

Activity (act) diagrams are used to show the process for creating and releasing the Manufacturing Plan information to labs and factories. These entities follow these plans to complete work to meet their requirements or objectives. It is also used to show the process to create the assessment and assignment of the MRL value onto items and the relationship of items to a manufacturing location, whether in a lab, internal factory, or external to the organization.

Tables

Tables are used to organize and illustrate some of the objects and associated attributes for the model rather than creating complex diagrams. Completing the creation of the model leads to determining a set of Object/Attributes which could be valuable in determining MRL Values for products in development. Table 2 shows just a few of the sub-threads of the overall table created to cover recommended object/attributes for all sub-threads. In the course of ongoing work in the development process, these sets of values were reviewed with colleagues working on same or similar projects; feedback on

the objects/attributes were selected as well as to get input on any other possible object/attribute that should also be considered.

Table 2 - MRL Sub-Thread Objects/Attribute Sample from MBSE Model

Feedback/Input on Artifact Objects Associated with MRL Threads		Instructions - Feedback Requst	Feedback Ratings: 1. Not at all Useful for MRL Rating on this Sub-Thread 2. Not Very Useful for MRL Rating o this Sub-Thread 3. Useful for MRL Rating on this Sub-Thread 4. Very Useful for MRL Rating on this Sub-Thread 5. Absolutely Required for MRL Rating on this Sub-Thread						
MRL Evaluation Threads	Handbook Reference#	MRL Matrix Sub-Thread	Valuable as Artifacts Object or MRL Rating Source?	Feedback Rating (1 to 5)	Measurable Attributes to Track on Objects	Attribute Value Scale	Full Rate Production MRL 10	MRL Level 0 - 4	MRL Level 5
A Technology & Industrial Base	A.1	Industrial Base	Manufacturer Selection (MFG Plan/Purchasing Orders)		Create/Update MRL Value on Part Number to Manufactuer Location	MRL by Criteria	Deliveries at Full Rate Production	**Target on MFG Plan**	**RFQ or PR Created**
	A.2	Manufacturing Technology Development	Comodity Code (Item Manufactured vs Source Approval)		Commodity Code of Part matches Commodity Code of Manufacture's Rating	No, Proposed, Yes	Yes, Approved	**Proposed**	**Proposed**
B Design	B.1	Producibility Program	DFMA Score of Design Item (PDM)		Design For Manufacturing Assessments if required by MFG Plan for each PN	N/A, Planned, Done	N/A or Complete	**N/A or Planned**	**N/A or Planned**
	B.2	Design Maturity	Technical Readiness Level (TRL) of Design Item (PDM)		Technical Readiness Level (TRL) assigned on each associated TDP Object	Per TRL Scale	TRL 9	**TRL 4**	**TRL 4**
C Cost & Funding	C.1	Production Cost Knowledge (Cost modeling)	Target Cost for Item by Marketing or Customer (RFP/RFQ)		Percent of Cost for Lot as compared to Cost Target in MFG Plan for Phase	Cost per Unit Planned	</= Target Cost	**Cost per Plan**	**Cost per Plan**
	C.2	Cost Analysis	Quoted/Actual Cost versus Target (Purchase Contracts)		Percent of Cost for Lot as compared to Cost Target in MFG Plan for Phase	Cost per Unit Planned	</= Target Cost	**Cost per Plan**	**Cost per Plan**
	C.3	Manufacturing Investment Budget	Capital Investments Planned/Committed (Contract/MFG Plan)		Percent of Cost for Lot as compared to Cost Target in MFG Plan for Phase	Cost per Unit Planned	</= Target Cost	**Cost per Plan**	**Cost per Plan**

Feedback Incorporation

Once the model was fully developed and the set of objects/attributes of MRL evaluation criteria were completed, a spreadsheet was prepared to provide an overview of the modeling process with instructions on how to review two sheets in the workbook. One sheet contained some preliminary values and feedback was requested as to the value of a given criterion, and the associated object/attributes that could be used to determine an MRL value for a given sub-thread of the assessment methodology. The reviewer was asked to rate each one on a scale of 1 to 5 with these ratings representing:

1. Not at all Useful for MRL Rating on this Sub-Thread

2. Not Very Useful for MRL Rating on this Sub-Thread

3. Useful for MRL Rating on this Sub-Thread

4. Very Useful for MRL Rating on this Sub-Thread

5. Absolutely Required for MRL Rating on this Sub-Thread

A second sheet was developed for providing input back to the researcher for recommended criteria and associated object/attributes for each sub-thread that was not considered or indicated in the previous sheet for feedback. This sheet permitted open-ended input to be provided. Colleagues were asked to use the same ratings on usefulness of the suggested items as was used on the previous sheet for feedback.

An associated MS Power Point Slide Presentation was used with the feedback tool in several sessions to review the Modeling Process overview of the thesis project and the overall MRL Deskbook process as compared to the output from MBSE model being created. Colleagues that were included in this review process were from the various disciplines involved with the development process including, Program Managers, Operations Managers, Quality Managers, Systems and Design Engineering, and Manufacturing Engineering. In some cases, there was a full hour presentation review in conjunction with working on the development of Manufacturing Plans for development work in progress or being considered. In other cases, just a brief explanation of the thesis project was provided with an email or link to the files provided with a request for feedback or input as the thesis model and document were being finalized. Whether a formal written response, or just conversational feedback was provided, this was considered and enabled additional refinements of the model.

Overview of System/Case Study Modeling

As part of the modeling process, concepts were first drafted in simple diagrams using Microsoft Power Point and standard icons available in that application. These diagrams were then modeled in the MBSE software. Using the V Model from the Literature Research as well as notional Information Flow, the first step is to determine where MRL Assessments fit in the process as well as the objects involved in the information flow.

The MBSE activity diagram shown in Figure 9 shows the process used for developing the model as well as refining it with feedback and input from colleagues. There are several diagrams of the same type for different parts of the model. The flow does not necessarily indicate a single sequential path for the model development. The design is iterative, working the various diagrams in parallel, until the full picture is understood.

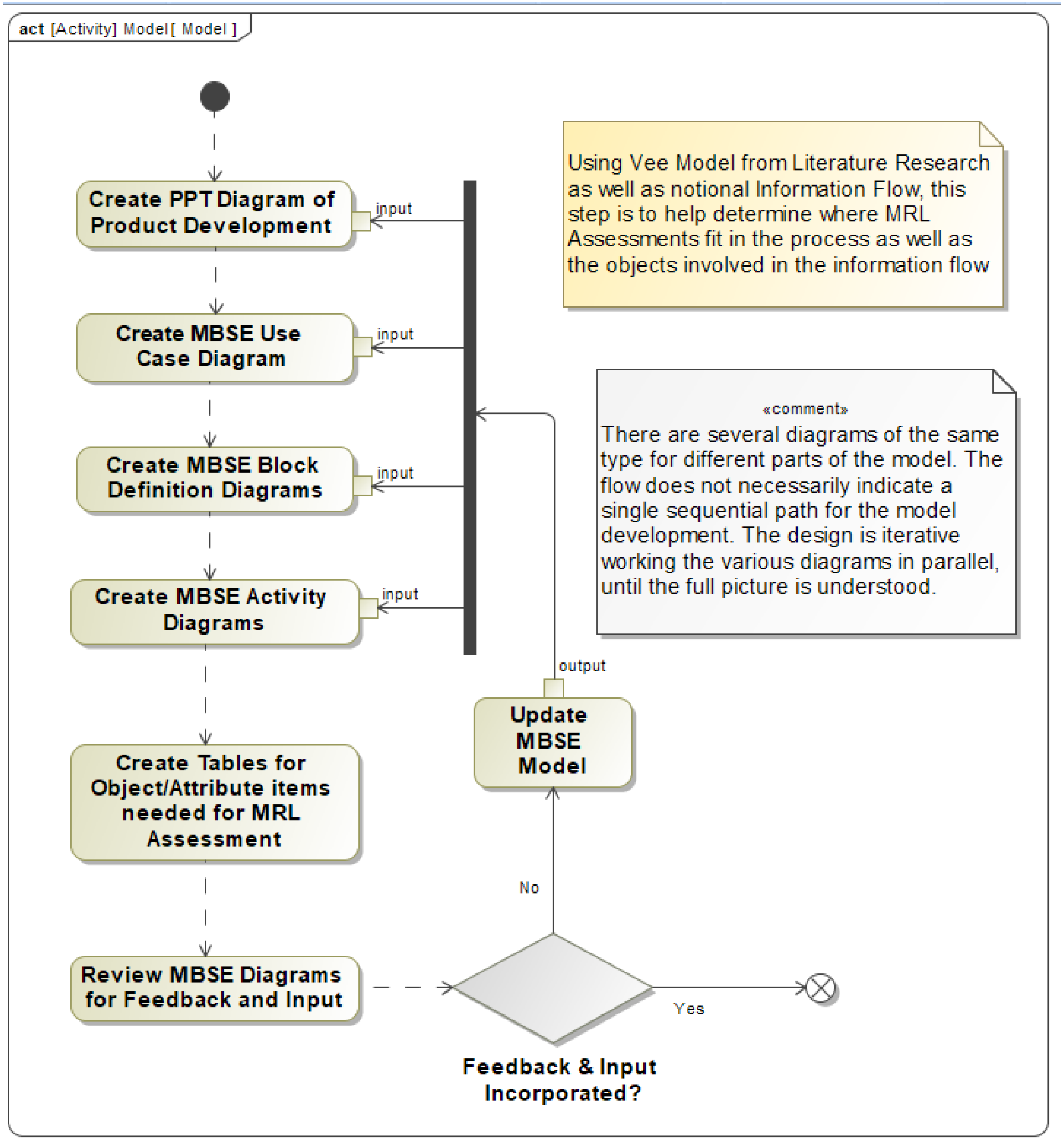


Figure 9 - Overview of Modeling Process Methodology

IV. Model Development

This section will review the process steps used for the model development. These include reviewing the development process for objects generated by during the process and how information from those objects may be used in subsequent steps. In particular the Manufacturing Plan was examined regarding its various elements and information that would be expected to be included in it. In addition, the process steps for the Transition to Product were examined in relation to the information that would be included in the Manufacturing Plan.

In addition to the objects created and process steps, an examination of organizational roles needed to support the transition to production were examined. Roles were included in several different diagrams for use cases, activity, and block definition diagrams. Besides the processes and objects, the organization roles help determine the resources needed to mature the manufacturing capability and readiness.

With the process information flow and roles understood, the remainder of the modeling process involved determining which attributes and information needed to be available from the model in order to assess MRL values. The ability to rapidly assess and monitor MRL depends on having the information needed easily accessible.

Information Flow Definition and Manufacturing Plan

The first step in the modeling process was to evaluate typical elements and object artifacts that are created in the development process and to organize their flow using a Why, What, Who, When, Where, and How approach to determine which objects were

used to answer each aspect of the development process. Figure 10 was created as the first organization of such objects:

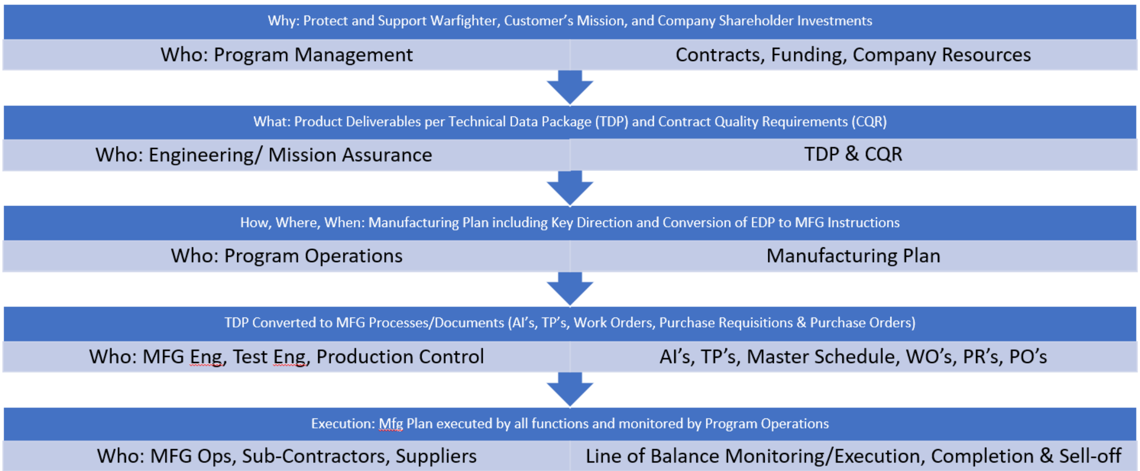


Figure 10 - Information Flow for All HW Product Builds

The information flow approach helped show the flow of artifacts within the process along with who may be responsible for creating each of those objects. The next step was to map the process flow for the objects as shown in Figure 11. The items enclosed in the red box are the items that are associated with and addressed in a Manufacturing Plan. Elements of the Manufacturing Plan determine which of the objects are needed and where they will flow to facilitate manufacture of the parts and assemblies.

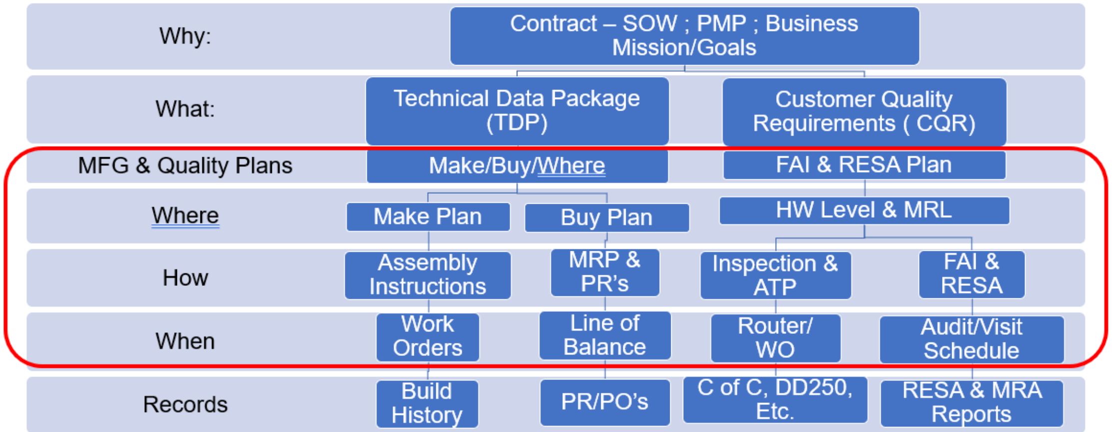


Figure 11 - Program Operations – MFG Plan Implementation

The Manufacturing (MFG) Plan is typically produced in later phases of a product development, when there is product to be delivered for early testing or initial operational evaluations. It details the various key processes involved in procuring material, assembly of product, integration and testing, as well as final product shipment to the customer. It provides the guidance to all of the operations and supply chain personnel needed to execute the building to defined configuration requirement. It is generally not required by customers during the earlier development phases for Materials Solutions Analysis (MSA) or Technical Maturation Risk Reduction (TMRR) phases of the development as there may not be a firm requirement to use for the build process of prototypes and preliminary assemblies.

Although perhaps not required as a deliverable to a customer, the MFG Plan was revealed as a key object with most of the information needed to determine the appropriate MRL should be at for any given stage of the life-cycle or at least at the Full Rate

Production (FRP) stage of development. Therefore, the MBSE modeling was started by examining it and its key components in a BDD as shown in Figure 12. This diagram shows the decomposition of the Manufacturing Plan into its major sections that correspond to the areas of focus in the plan that must be developed such that all requirements from the TDP, Statement of Work (SOW), or other requirements documents are considered and included in the elements of the plan.

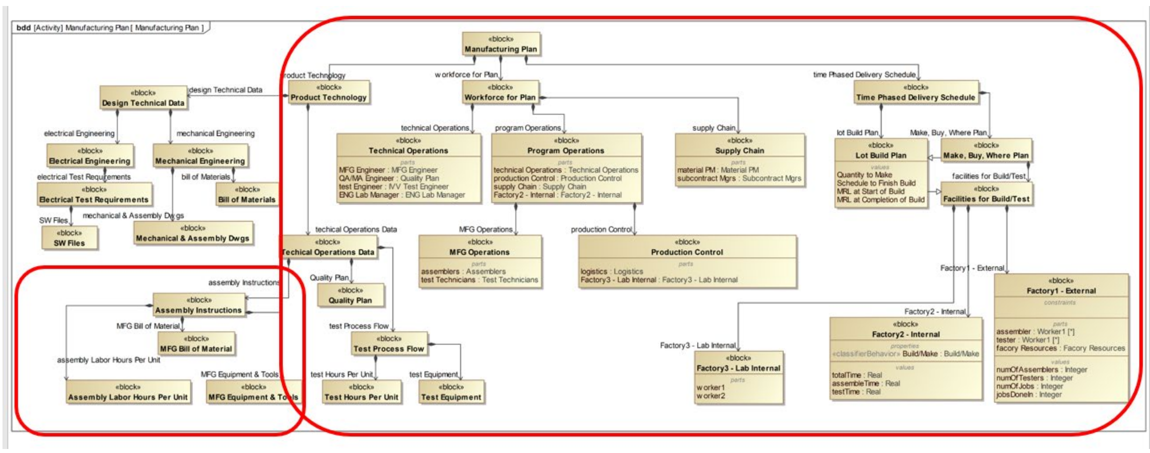


Figure 12 - SysML Block Diagram Chart – MFG Plan Implementation

The plan must address the technology regarding the maturity of the technical design or TDP as well as the Technical Operations processes regarding Assembly and Test instructions that describe the manufacturing processes and flow needed. The Workforce portion of the plan describes the amount of direct and indirect labor required to produce the quantity of parts and assemblies need in the various phases of the development and full rate production across the life of the product.

The Time Phased Delivery schedule provides not only the quantity needed, but breaks that down into phased milestones and maturity levels required of each build. The

resulting schedule combined with the Technical Operations information concerning resource requirements help determine the Make, Buy, Where decisions, designating where each physical part or assembly will be produced. The Manufacturing Plan must not only indicate the MRL requirement at each build phase, but also the actions and plans needed to advance the MRL to the maturity needed for Full Rate Production (FRP).

Transition to Production Process Activity per Manufacturing Plan

Once the Manufacturing Plan has been developed, the Transition to Production process begins with the activities of the Manufacturing Engineering and Test Operations roles converting the TDP to Assembly Instructions, Test Procedures, and Test Workflow documents applicable for the location where the items have been selected to be built. In some cases, the TDP is provided directly to an internal or external supplier factory "as is" for the development of those instructions and processes directly at the site where the build will occur. Unfortunately, rather than speed things up, it can cause delays, when the process is not developed in the Engineering Labs where the development was being done. The model shows that there is a need for the development of the same instructions and procedures, although perhaps at a lessor maturity level, in those labs as well. This provides the opportunity for further Manufacturing Maturity during the development process in the labs.

The diagram in Figure 13 is the notional process for converting the Customer/Design requirements into TDP and then the subsequent phases of transitioning this information into the place where they will be manufactured. The blue arrow between

the middle groups represent the typical “throw it over the wall” approach, where there is little active planned work performed to improve the MRL prior to the factory start up just after the TDP has been finalized.

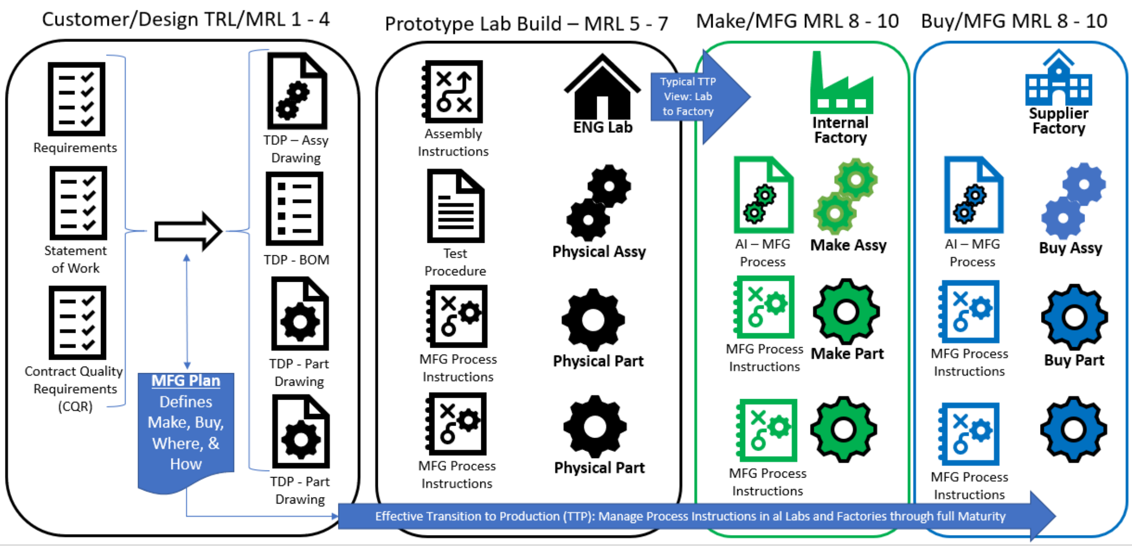


Figure 13 - Transition to Production – Process Objects

This activity was incorporated into the MBSE model, which is shown as an Activity Diagram in Figure 14. This representation was created in the model to indicate the flow of object/attribute information during the development process. One of the key things this diagram shows is that the work is essentially the same whether the information goes to a lab, an internal factory, or an external factory. Because the design engineers are also in the labs, it is often believed that they can handle the prototypes or other early non-deliverable engineering built units without the additional MFG Engineering and Test Operations Engineering support or additional expense. Unfortunately, although they perform some of the necessary tasks, they often do not produce the documentation necessary to transfer that knowledge to others in production. Therefore, although they

build these early products, the MRL is not matured or advanced adequately without the added discipline and focus on the process necessary to construct the products.

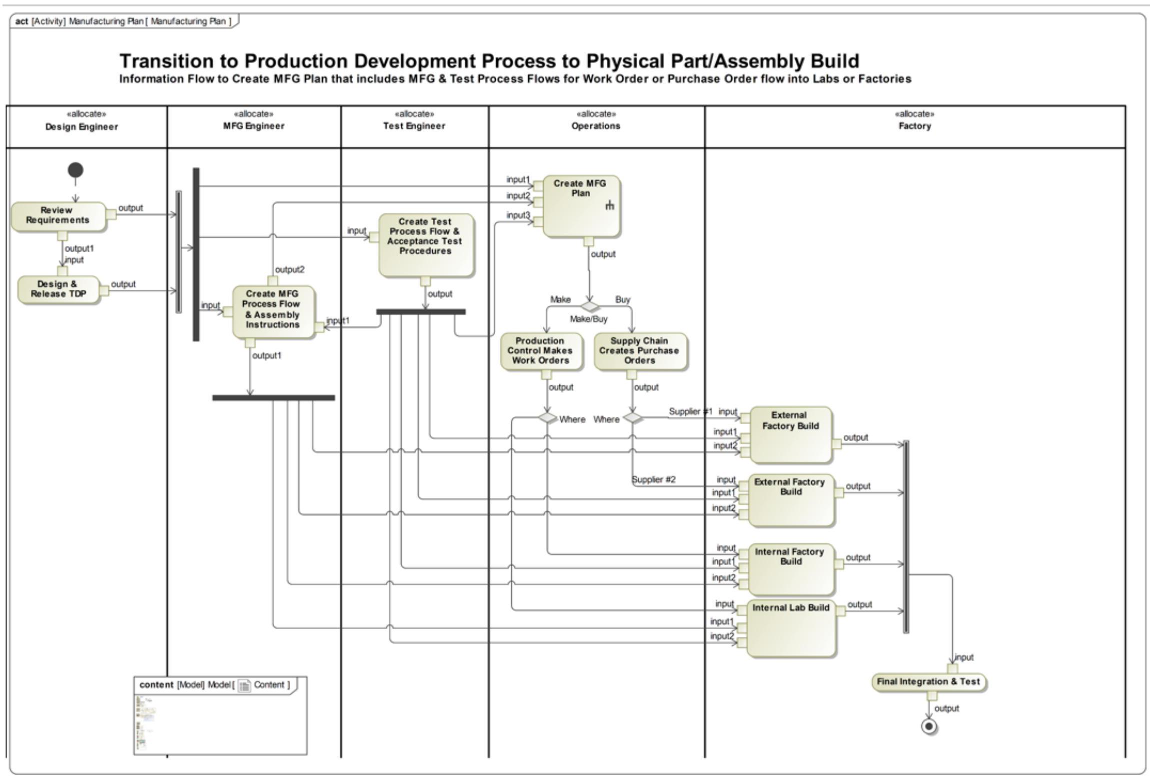


Figure 14 - SysML Activity Diagram for MFG Plan transition to production

Organization of Roles Needed to Support the Transition to Production

Another observation from the diagram in Figure 14 is the presence of roles at the head of each swim lane to indicate responsibilities in the transition to the production process. As shown, these roles include Manufacturing and Test Engineering, as well as the Operations manager. The diagram is shown as a single direction flow without any feedback into the beginning of the design. This is because it is only indicating a single build run. In reality, there ae multiple times the product is built during the development

process, and it is assumed that there is feedback between each build. However, there often is not formal feedback process or object. This was understood later, when determining how the build should be assessed and data incorporated into the model.

To further explore the roles needed in the process, the V model discussed earlier was overlaid with the use cases and actors involved in the development process. The diagram in Figure 15 shows some of these roles and where they are involved within the systems engineering process.

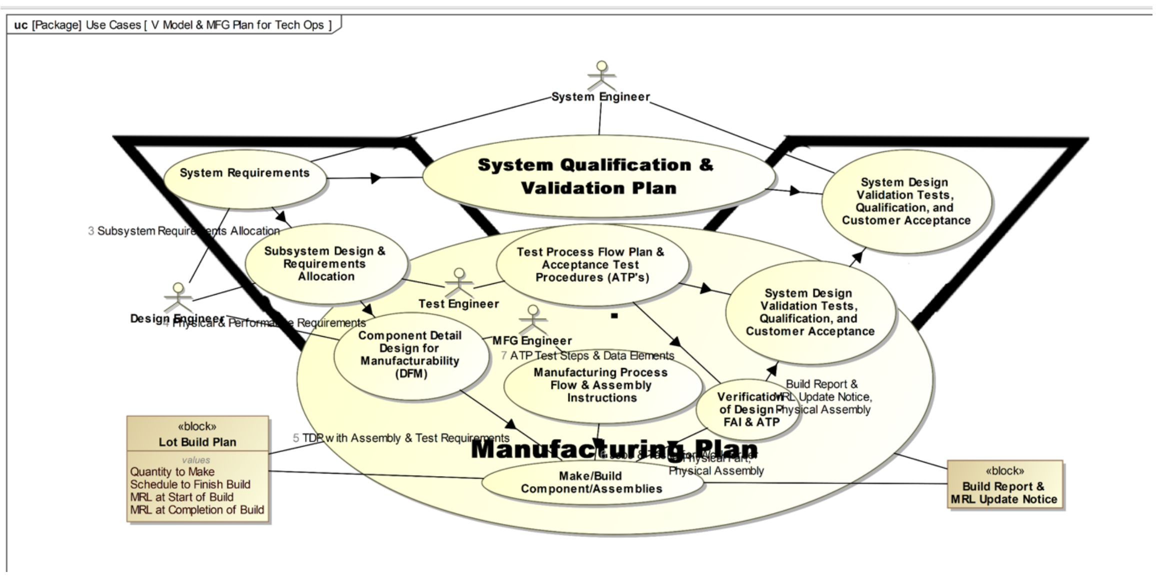


Figure 15 - V Development MFG Plan for Tech Ops

With some roles are identified are being needed to create objects as part of the Manufacturing Plan, it was decided that the model of the overall organization supporting the process to transition to production should be modeled. First, the Transition to Production diagram in Figure 13 was updated as shown in Figure 16. The added detail is in the role assignments for the work up at the top of the four sections. The grey colored

box above the second section for Develops Lab Processes indicates that the MFG and Test Engineering roles extend with arrows across the whole process to influence the design as well as transition the product builds into the production sites. It is clear that the Chief Engineer and associated design disciplines are responsible in the first block to the left during development of the TDP. Likewise, the MFG & Test Engineering disciplines are well understood to be required in the internal or external factories. Importantly, the transition phase is conducted in the second section to the right of the first one, where work is being performed in the Labs. Whether prototype builds or initial production units from an EMD phase occur during the transition, there is a need for Operations as well as the MFG & Test Engineering roles during these transition phases to begin to standardize production processes. There are arrows extending from this block for those roles to the left and to the right to indicate that these roles have to interact with the roles and processes to the left and right to provide feedback or generate plans for the successful transition.

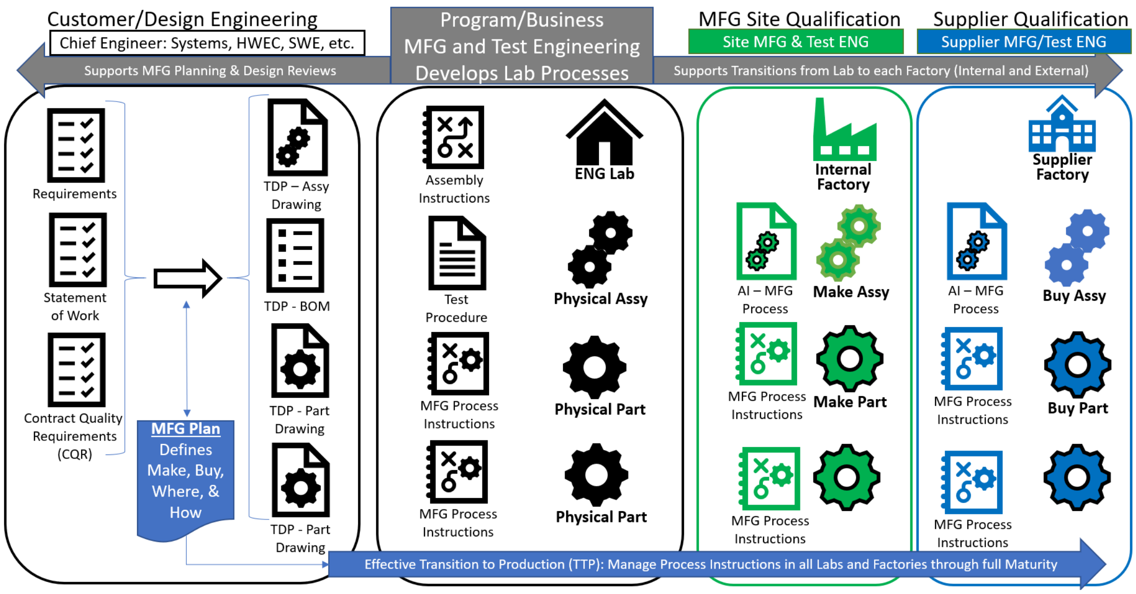
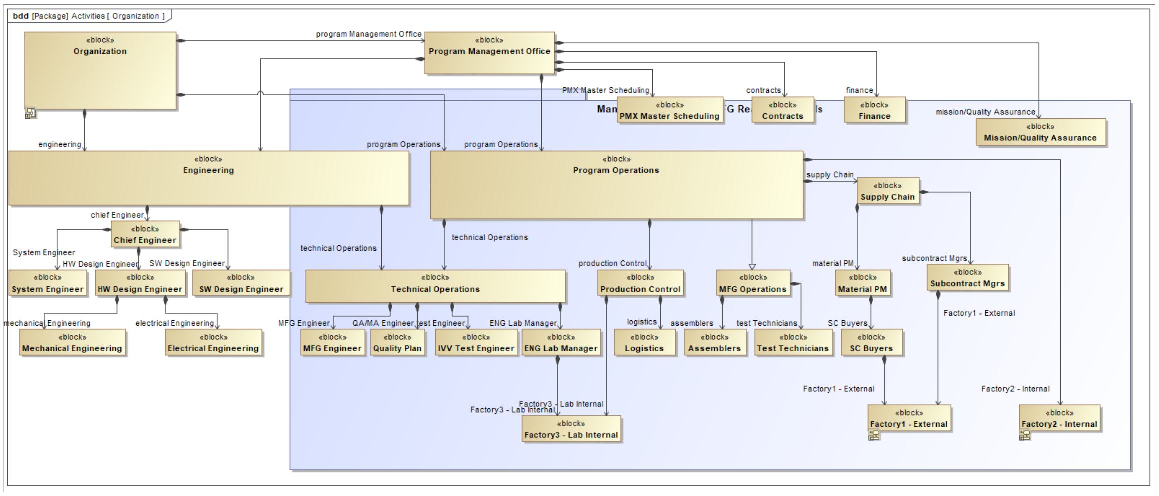


Figure 16 - Transition to Production – Process Responsibilities

Figure 17 incorporates multiple roles and functions into the model to show interactions and dependencies for the development team. One key insight from the model is that the Manufacturing and Test Engineering roles in this model are an extension of both the design engineering group lead by the chief engineer and the Operations Manager. This is because the objects or artifacts produced in the Technical Operations group are guided by both functional disciplines. The engineers in these Technical Operations roles must incorporate requirements and direction from both the Engineering stakeholders concerning the system and other technical requirements, as well as the requirements from the Operations manager to comply with the Business and Manufacturing Plan developed for the product.

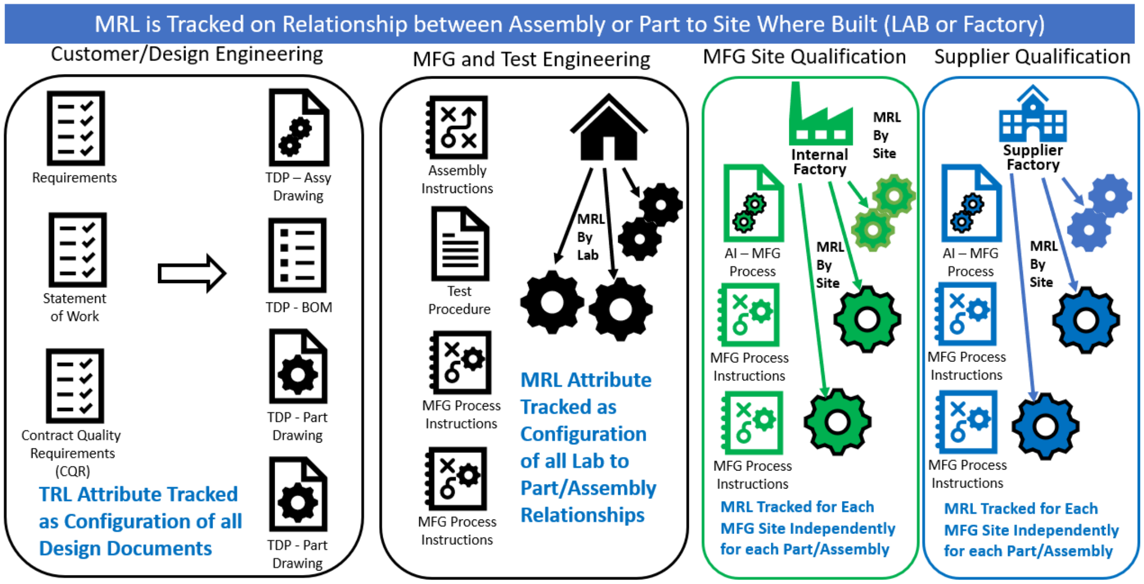
The actual organization and reporting structure may vary from organization to organization as to whether this Technical Operations group reports to and is managed by

the Engineering function or if it is part of the Manufacturing and Operations functions or departments.



Where Should the MRL Value Be Tracked in a Database?

Now that the model has explored and discovered some of the objects and elements in the development process associated with the transition of products to production, further modeling is needed to determine where to track the MRL values. Prior to diving into the SysML diagraming for the model, the logical place to record MRL values was considered in Figure 18. It is seen that each location where a product may be built during development needs its own set of instructions and procedures for each product to be built. As such, the maturity level can vary at each build location. Therefore, the MRL Value cannot be associated only with the product, as may be the case for the Technical Readiness Level value. TRL values are associated only with the design of a product and not where it is built or the MRL of the location to build it.



Since MRL values can vary from site to site, the attribute for the MRL value must reside at the relationship between the part or assembly and the location where it is built. Most product is developed and initiated at a single manufacturing site. However, for FRP, there may need to be multiple factories or sites building product to meet demand. In addition, once the design has been finalized, there could be multiple reasons why the production would be transitioned to another manufacturing site. As such, its MRL would need to be assessed independently from the original site where the product was first launched.

Since the overall MRL value for an item or manufacturing site is determined by the MRL value of the nine sub-threads, some consideration is also sought as to how those sub threads can be assessed and where the associated attributes with those sub-threads could be stored. So, another diagram was made to understand where the sub-tread

information could be stored and examined. Figure 19 shows how planning leads to determining the associated resources required and how to communicate that to the build locations. In this model, the information flow was designed based on what is needed to assure the manufacturing site will be able to prepare itself to meet the schedule determined from the requirements.

Many of the MRL sub-threads are associated more with a location regarding its readiness to produce items than necessarily information regarding the product itself. Key items to consider are resources available regarding space, equipment and its capacity versus volume and schedule the product demand will have at full rate production. Beside facilities and equipment, Human Resources are also important regarding skills and training as well as the amount of labor available. It was determined that there needed to be a way to capture this in the model as well.

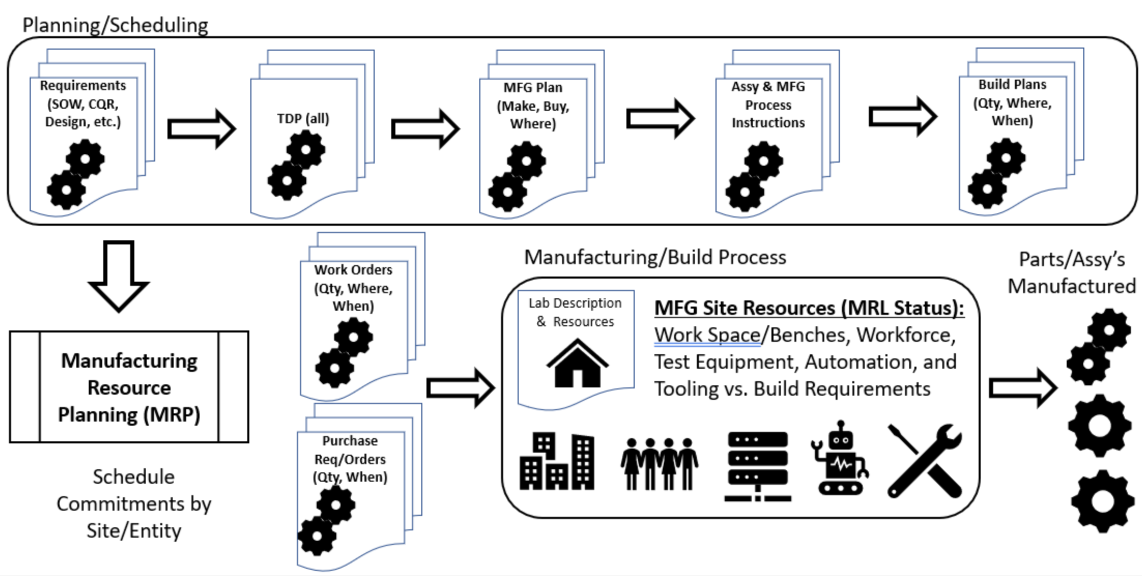


Figure 19 - TTP MFG Readiness – Information Process Flow

These notional diagrams were considered when developing Figure 20, which shows that MRL may be determined by the relationship between the component or assembly being built and the lab or factory which builds it. Besides identifying the objects and attributes that would be needed in the model to record MRL values, there needs to be an assessment process that will occur during development. This assessment process yields current MRL values and an understanding of existing gaps which need to be filled to achieve the desired MRL value.

MRL Assessment Methods

Having an event with a team to do a Manufacturing Maturity Assessment (MMA) for a single part/assembly within a structure or system at a manufacturing site is one way to determine the current MRL value for parts or subassemblies. This is the typical way the MRL is determined and includes the gathering of objects and data that support the assessment. It is also an opportunity to see what may still be missing to get to a desired maturity level, such that action plans can be assigned and developed.

By completing a Build MRL Report with the same resources responsible for building the product at the completion of each build, a team working on the transition to production can plan the objects needed and perform the assessment as a routine part of their job. The routine development of such a build MRL report would provide visibility of the current MRL and associated risks that may be pending mitigation

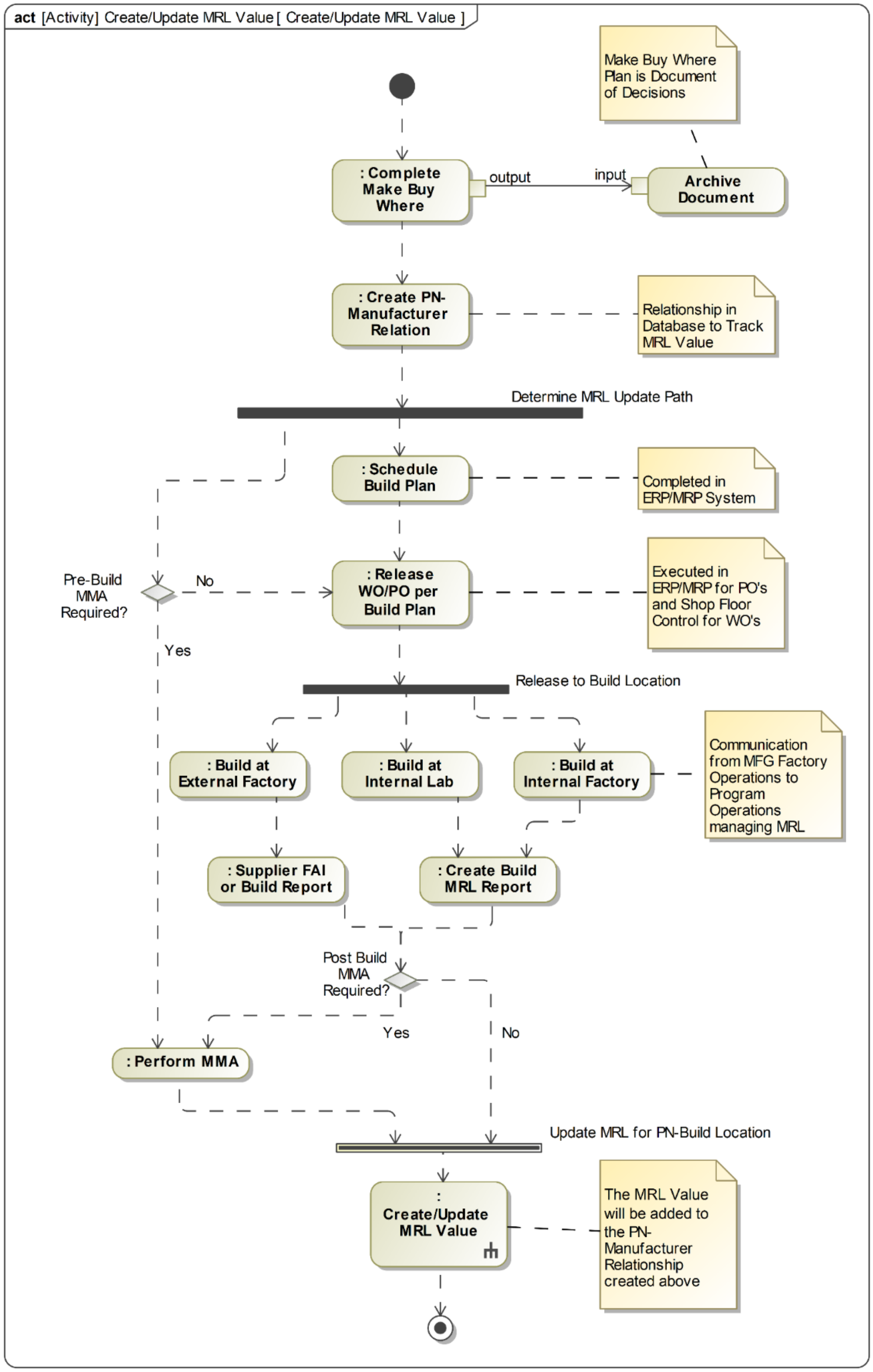


Figure 20 - SysML Activity to Track MRL on Part/MFG Site Relationship

MRL Attribute Status Tracking Location

Figure 21 shows where MRL Attributes are stored in a Database to Track Progress. The first and primary part of the model is to show that the Physical Assembly item must be related to a factory where that item is to be manufactured. The MRL value is an attribute on that relationship, that is the MRL is an attribute which is associated with a particular part when it is constructed in a specific manufacturing process. Therefore, it is not associated with either the part or the process but the relationship between them. The other aspect needed is the ability to store information regarding the resources available in a manufacturing site. Regardless of whether the MRL level is being determined by an MMA or through a Build Report review, the assessment of the needed resources is a key part of determining the MRL value. As such, the model needs to include gathering and recording that information.

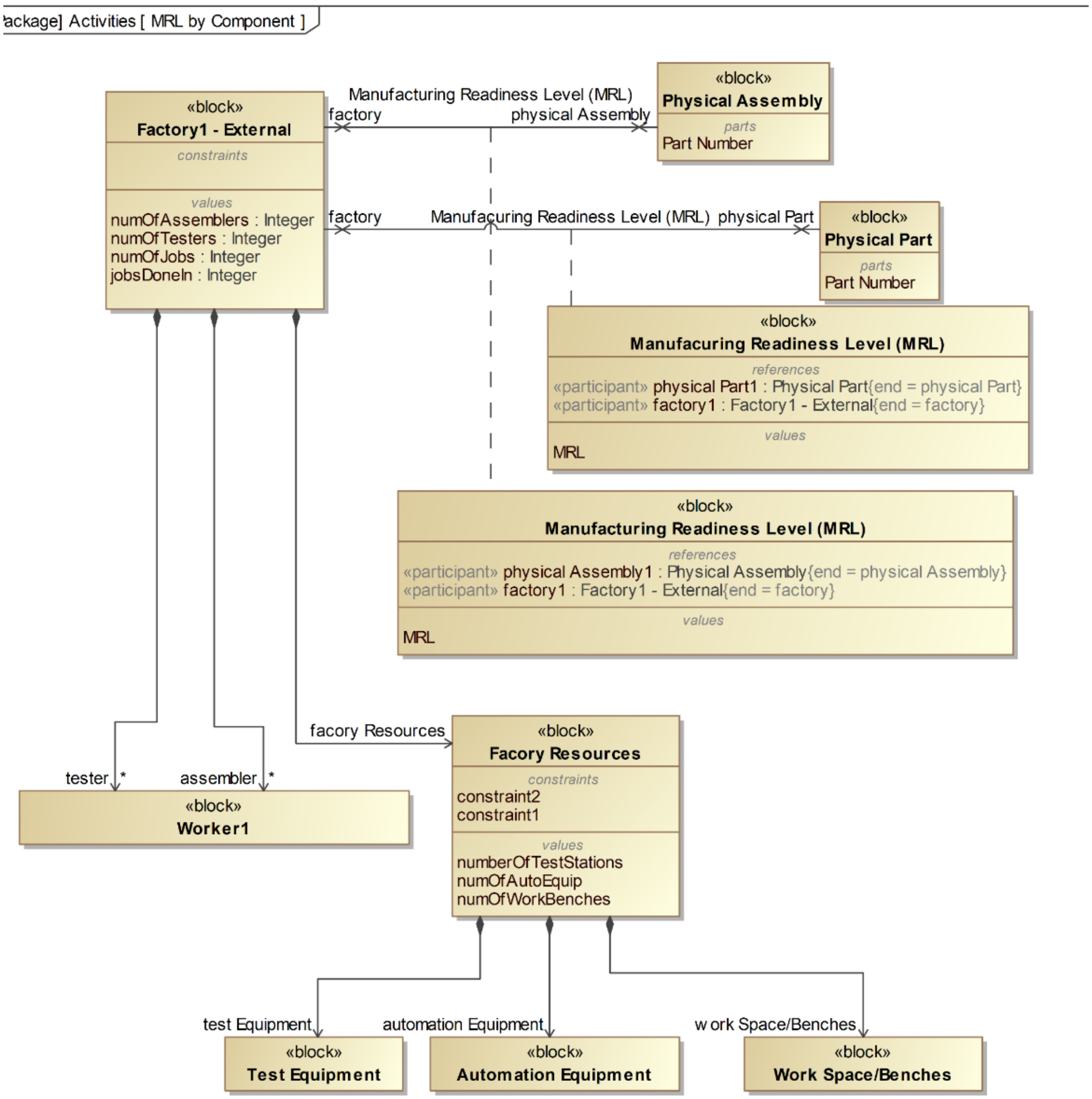


Figure 21 - SysML BDD Model to Track MRL on Part/MFG Site Relationship

Summary of Chapter IV

The modeling of the development process for the purpose of this research focused on determining which objects and associated attributes are created that contain information required to determine MRL values in at least one of the sub-thread areas. In order to do that, the overall process flow was considered along with the various roles involved in creating or processing the information. Therefore, an information flow was determined to indicate when and where the objects/attributes were created and by whom.

In addition to having objects created and flowed as part of the maturation process, it was also necessary to determine the natural evaluation steps in the process. Knowing when and where there is an opportunity to evaluate and record changes in the maturity of an item or MRL criteria enables the self-assessment needed to manage achieving the MRL level desired during development.

With the object/attributes identified and the evaluation method determined, the model can show how the key information can be placed into data records in a system to enable easy access to the status of those items dynamically. Development teams are able to perform routine assessments of MRL levels without having a larger assessment event.

V. Results, Conclusions and Recommendations

The research of this thesis is focused on finding the method and available information generated from the normal development process that would enable accelerating the transition to production by internalizing the Manufacturing Maturity Assessment process used to determine the Manufacturing Readiness Level of products throughout the life-cycle. Using the Model Based System Engineering approach, a model was created that enabled answering the research questions as described in the following paragraphs. Therefore, the research objective is considered achieved.

Description of Analyses Process

The attributes which should be tracked to permit a more continuous assessment of MRL were developed by working through the Product Development use cases, activities, and information objects produced as well as considering the organization roles involved as actors in the process or stakeholders in the results. The model creation had its purpose to find answers to the research questions.

The principal analysis needed from the model was to determine if a set of attributes associated with objects within the model could be included in such a way that a set of MRL assessment criteria could be developed into tables that align with the MRL Deskbook definitions of maturity and readiness for manufacturing

Reviewing the resulting tables with colleagues served as a method to continually refine the model. The feedback and inputs received represented an informal information

gathering approach and were applied to broaden the perspective of the modeling with multiple disciplines of stakeholders incorporated.

Determining the Key Attributes to be included in the Model

As mentioned earlier, there are nine sub-threads used to determine the overall MRL value for items. Table 3, shows the MRL Factor of each sub-thread with its description and a notional set of objects and attributes that could be found useful in assessments and determining MRL Values. Clarifying these objects and attributes further would enable extending the model into a development process or Manufacturing Plan to assure that the data is produced and recorded in the course of the development process.

Table 3 - Mapping of MRL Threads to Information Objects and Key Attributes

MRL Factor	Factor Description	Object with Information	Key Attributes
Technology and Industrial Base:	Capability of suppliers to support production of components/subsystems.	Part/Assy relationship to identified Lab/MFG Site/Supplier	MRL Level of Part/Assy for that Entity based on performance.
Design:	Identification, and control of Key Characteristics.	KPC identified in TDP for all Part/Assy in the design	TRL of TDP
Cost and Funding:	Examines the risks associated with reaching manufacturing cost targets.	Project Budget and Schedule and EVM	CPI/SPI for project
Materials	Risks associated with materials.	Line of Balance	Total Cost of BOM per PO's & Delivery per MRP
Process Capability and Control:	Risks that the manufacturing processes are able to reflect the design intent of key characteristics.	MFG Plan and MFG Process Document indicating MFG Capacity, Cycle Time & Yields	HPU Standard & productivity, Total Cycle Time, First Pass Yields, Scrap/Rework Costs
Quality	Risks and efforts to control quality.	Inspection and ATP plan	Yields, SPC, Cpk per spec's
Manufacturing Workforce (Engineering and Production):	Required skills, availability, and number of personnel to support the manufacturing effort.	MFG Plan and MFG Process Document indicating MFG Capacity, Cycle Time & Yields	HPU Standard & productivity, Total Cycle Time, First Pass Yields, Scrap/Rework Costs, Number of Trained available
Facilities	Capabilities and capacity of MFG facilities	MFG Facility Description Doc	Process Capability/Capacity
Manufacturing Management	MFG Plan to translate the design into an system meeting Program goals	MFG Plan including Ops & Support Staffing Plan	Actual hours of support by each function required

Feedback and Input Incorporation

Most of the feedback suggested minor adjustments in the course of creating each diagram. Therefore, there was not a tabulation of the amount of input and feedback received in the course of the model development. There were a few modifications that are worth covering in some detail here as examples of how the feedback helped influence and refine the model. They help assure that the model is not limited to a narrow perspective, but consider the whole life-cycle of the development.

Quality Plan Management for Manufacturing Readiness

One of the items regarded the placement of the Quality Engineering and Quality Plan in the organization roles and Manufacturing Plan development. It was stated that Quality Management and Plans cover a broader role in the organization and process than just at the manufacturing level. As such, the Organization BDD in Figure 17 was updated to show Mission/Quality Assurance at a higher and broader level as would be associated with a Management System and procedures implemented to meet standards such as ISO9000 (or AS9100 used in the Aerospace Industry). However, the Quality Engineering role and associated Quality Plan are still shown in the Technical Operations Role and the decomposition of the Manufacturing plan in Figure 12.

The scope of the model does not cover all of the Quality Management System and its processes; instead, it is focused on assuring the detailed information is transitioned to production from the technical operations functions of Manufacturing, Test, and Quality Engineering work. In this case, the Quality Plan of the model implies that it is a focused

plan for a particular part number or component/assembly with its own unique quality requirements in the process. Examples of these details would be specific inspection points in the process, implementation of Statistical Process Control (SPC) charts at certain process steps of the workflow, and recording certain test data attributes for acceptance criteria.

Often, the Quality Engineering professionals may be seen as having broad oversight to assure compliance with processes and customer or contract quality requirements; however, in this model, more is required. There needs to be much more specific product understanding and direct input and feedback regarding the quality control methods needed in the manufacturing and test processes and procedures.

Manufacturing Readiness Continuation Post Achievement of MRL 10

During Supplier Assessment for a second source manufacturer of an assembly needed for product entering the Full Rate Production (FRP) phase, it was pointed out why there was so much emphasis and oversight by the Raytheon team when conducting the manufacturing readiness assessment. For this particular assembly, all of the previous builds from initial prototypes Risk Reduction units, Engineering and Manufacturing Development (EMD) units, and Low-Rate Initial Production (LRIP) units were built by the same manufacturer. When it was time to schedule the Full Rate Production (FRP), the supplier "No Bid" the full quantity needed. The "No Bid" indicated that the supplier did not want to make the investment needed to increase their capacity to the full production rate. It was determined, that although they had worked to develop the assembly for

several years, it really did not fit their business model or factory for providing the high-volume rate needed. They were willing to continue building at the same rate supplied earlier in LRIP, but could not ramp up to the volume needed by Raytheon and the customer. As such, two additional secondary sources were being developed.

This is not an unusual case, especially when there is encouragement to use smaller companies to provide opportunity to them in the Defense Acquisition Industrial Base. Most companies desire the development of second sources to assure a reliable supply chain once in production. However, this example highlights two key things to consider when developing and managing the Manufacturing Readiness Level of parts and assemblies.

1. The MRL value of a part or assembly is unique to the Manufacturer of the item.
2. The MRL Level of a higher-level assembly will change over time and potentially at each build of the product considering all of its components and subassemblies

Therefore, it is very important to realize and understand that the Manufacturing Readiness Level assessment and management process does not end with the first completion of a transition to production resulting in an MRL 10 rating for the Full Rate Production. Instead, each subsequent build while at FRP must be examined for the following situations, especially for the assemblies that have been outsourced to suppliers.

- New Product Introduction (NPI) subset plan where small quantities are built for insight to future manufacturing yields
- Supplier and Sub-tier capacity analysis for potential future volume increase

- Nonconformance returns from your customers and Root Cause & Corrective Action (RCCA) plans – strategic feedback loop for bulletproof product quality optimizations
- Technology enhancements through lessons learned incorporation on new designs prior to NPI builds – Design for Manufacturing (DFM) strongpoint
- Engagement with commodity specialist (Supplier) for DFM input and proactive optimization of production yields

At the conclusion of the Supplier Assessment, the team emphasized that although the supplier had not been through all the previous phases, they needed to be producing at an MRL 10 level from the beginning for the higher-level assembly to be able to continue to meet its MRL 10 level. Therefore, the transition work never ends until well past the production phase and while the product is still in service. Performance Based Logistics for products in service often requires additional production of subassemblies or spare parts to keep the product operational throughout its service life. There are always Diminishing Material Supply (DMS) concerns to address and contend with that result in new designs and builds during the phase. It is imperative that such new assemblies achieve the high MRL levels quickly, since the systems are already in service and critical to ongoing operations.

The model was focused on the Transition to Production during the Product Development phases, and thus not for products already in production. In addition, it is assumed that each factory, whether internal or external, has the appropriate Technical Operations Resources to engage in the transition. What was not highlighted in this model

was the involvement of Supplier Quality Engineers or others focused on assuring sub-contractor manufacturing readiness. It should be assumed that the same resources are needed for each manufacturing site.

Summary of Research Gap, Research Questions and Answers

In this section of the conclusion, each of the research questions from Chapter I are listed with the specific answer to that question as determined from the research. Although, there is not a data analysis section due to the limited scope of the research, answering these questions successfully was the goal. They can be answered with the limited scope of the model developed during this research.

Answer to Question 1

What are some specific objective elements that can be monitored or tracked concerning specific attributes or characteristics that can provide a current MRL status assessment of an item for projects in the Engineering and Manufacturing Development (EMD) phase?

Multiple objects were created in the MBSE model shows there are key elements needed for evaluation the MRL status generated in the course of the development process. These can be used to evaluate some of the of various sub-thread elements. Some of these are likely in the form of documents, such as assembly instructions and test procedures. Others are database records such as purchase orders to suppliers that contain cost, quantities, delivery dates, and other searchable information which are often contained in an Enterprise Resource Planning tool or system.

The model developed also includes a few non-standard objects that could be used for such tracking, such as Manufacturing Plans, Build Requests, Build Report Assessments, or other object that may be used to store relevant information. The resulting table of suggested objects and attributes provides some examples to consider which may be the most valuable during development to better understand Manufacturing Maturity and any actions needed to move closer to the goal.

Answer to Question 2

Where do organizations manage objective elements associated with MRL status such as could be the system of record for status and values of the key attributes?

There are three key areas for systems of records in the manufacturing process for key attributes. A Product Data Management (PDM) is the typical system of record for the Technical Data Package to control configuration of items needed to meet the overall requirements. PDM or a similar system is also used for creation and release of Assembly Instructions and Test Procedures or Test Flow documents. Unfortunately, the PDM systems, although good for tracking the configuration and approval status of documents or other objects, often do not have many of the key attributes which were revealed as necessary metadata in the system. A Shop Floor Control (SFC) system used for routing tasks and jobs in a manufacturing system is where more relevant attributes are included, such as how many hours per unit (HPU) are needed to assemble a unit or perform certain tasks, what equipment or capacity exists in a work center, where work is routed, etc. The third area where the important attribute data are found is in the Enterprise Resource

Planning (ERP) system which is used for planning and procuring material needed for manufacturing.

Answer to Question 3

Can such attributes be accessed via an on-demand query into a Model Based System Engineering tool to determine an MRL value for any component/part, sub-assembly or sub-system in a product or system?

Each of the three major systems (PDM, SFC, and ERP) are routinely configured to produce output reports used to manage the development or manufacturing process. Whether or not they are available “out of the box”, any such database can have custom reports generated to output the set of attributes desired, as long as the team has been disciplined in collecting and storing the needed information.

The key to using the MBSE tool to calculate an MRL value for any aspect of the product or subassembly is to complete the model in such a way that the attributes and objects needed for such an assessment is built into the overall process of gathering and storing such data in the course of the normal work of the project/program. The effective management of the MRL of products during development requires that the assessment method and criteria be established up-front and that work is performed in such a way that the data flow that occurs is properly captured for assessments. If such a system were implemented, rather than spending time gathering such information for an MMA event, reports could be run and evaluated at each significant milestone or in weekly team meetings, where progress is assessed.

Answer to Question 4

What would a notional process, involving MRL assessments early, look like and how can that be used to inform production related decisions with impact potentially years in the future?

The key issue here is to know the criteria that will be used to rate the various aspects of manufacturing maturity and readiness to assure that the attributes needed to create the metric or scoring is built into database systems such that the appropriate data is collected to allow one to create the work orders for product builds. The attribute data then must be stored in a data record on a relevant information system versus embedded into a document object. Or at least, it should be accessible in both places (perhaps a hyperlink to the master record for good configuration control). The process used to create or schedule builds of assemblies for evaluations would include creating such records in one or more database systems. At the completion of the work order or build of a set of units, a build report would be run to capture the actual performance versus the plan that initialized the build. If the scoring criteria is either built into the system or some of the objects stored in records of the system, then the MRL could be calculated by the system and updated on the MRL attribute with the calculated value. This would be necessary for every part/manufacturer combination in the entire Bill of Material for the system.

Development teams would be able to see and determine if the manufacturing maturity was keeping pace with the desired schedule and rate of improvement. Having these metrics and details regarding the sub-thread aspects of the readiness, teams would

be able to schedule and perform any actions needed to accelerate the process from a MRL perspective.

Study Limitations

As indicated in Chapter I of the thesis, the model is focused on the development work needed to transition a designed product to production and does not include the design of the product to meet its technical requirements. In addition, the purpose of the research was not to define a specific assessment criteria or set of attributes to be used for MRL value determination, but rather assess the development process for the opportunity to create a conceptual model that could be further tailored to a given businesses product or deliverable item. It is not intended to prescribe a specific tool or set of attributes, but rather prepare the foundation for such work to be created.

Once a business or development group determines the most valuable evaluation criteria and attributes for their specific product, the MBSE model can be further developed to predict MRL values based on data that can be forecasted as expected results or calculated from the data of actual product builds.

The major limitation of this study is that there is not easily accessible data regarding the development process metrics used to assess MRL that is shared outside of a business. Reasons for the lack of this information include the nature of security around items used in the Department of Defense that limits access. Additionally, there is competition among major contractors and businesses that create the desire to keep such information proprietary due to the potential financial impact.

Recommendations for Action

There are three key areas for action in order to take advantage of the research and conclusions. These include examining information systems for storing/retrieving MRL values, determining the right organizational responsibilities to execute the MRL management focus, and determining the appropriate information flow for such assessments. Each business or organization may find they have some key structural elements in place, but could further optimize and accelerate their transition to production by examining ad adjusting their approach to one of the other areas.

MRL Value Database for Each Part/Assembly Build Location

The main recommendation from this research is that organizations consider and document their criteria to be used for MRL achievement at the various sub-threads and determine the process for storing the information in a database or repository such that the key attribute data can be easily extracted and used to analyze the development progress. It should not be assumed that because it is not clearly spelled out by a customer or sponsor in a Statement of Work or Request for Proposal, that MRL is open ended and measuring it is not required. There will always be some cost or resource issue associated with a project that will determine its viability for success and establish the overall value of the project to the stakeholders. Writing down these criteria limits and flowing them into requirements for MRL assessment criteria will enable project teams to do the appropriate level of planning and resource allocation to understand the value and risks of the project.

Once the criteria are well understood, there may need to be some database system improvements to capture the data associated with such activity. One key item is simply to assure that all build locations, whether in a lab, an internal factory to the business, or with subcontractors are established in one of the information systems of the project. Then the part/assembly relationship can be created to provide a place where the resulting MRL value can be stored and maintained with further development and maturation of the product and manufacturing process.

Many organizations use some form of an Approved Supplier List or Approved Manufacturer List as part of sourcing and supplier management. These databases can be a place where a higher level MRL value could be stored or maintained, but they may not be adequate to keep lower sub-thread assessment details. In either case, the process of adding or updating records in such databases should be considered together with a systematic approach to managing Manufacturing Readiness Levels.

Organization Responsibilities for MRL Value Management

As can be found in this research, the organization roles involved in Manufacturing Maturity Assessments are varied and cut across multiple disciplines and functions in an organization. It is important for those in each role to understand how and when to make their contributions. As such, the organization leadership team should establish the appropriate leadership necessary for the planning and execution of manufacturing readiness preparation activities. Although there are many technical tasks and activities involved, there are also many operations and administrative details involved in the

tracking and management of the information involved in the process. The model in this research focuses on the Manufacturing Plan with a Program Operations Management role leading that effort; however, each organization should determine the appropriate leadership focus needed to implement such an initiative.

MRL Maturation Process Flow

With appropriate evaluation criteria and organization structure established, an organization desiring to accelerate its Transition to Production during development should examine their current process and procedures to determine if the objects/attributes of concern are routinely being produced. It may be that there is useful information stored in documents, program reviews, and other artifacts that are difficult to locate or retrieve at the time important decisions are being made.

For information to be valuable, it must be readily available to the decision-makers at critical assessment points. A thorough examination of the organizations information systems with regard to object/attributes of value to the MRL Maturation process is valuable. The process flow of the organization should also include the appropriate storage of records to enable the rapid assessment of MRLs.

Recommendations for Future Research

Considering the Recommendations for Actions above, there are three areas which could yield very useful information from future research. These could include review of different Manufacturing Maturity Assessment Tools to determine the common criteria or attributes used for assessment. Additionally, research regarding attributes and

information associated with Approved Supplier or Manufacturer Lists at various organizations would be beneficial. Finally, another research project could possibly focus on organization structures and disciplines regarding transitions to production.

Summary or Significance of Research

There are three significant areas of significance from the research. Manufacturing Planning, although not formally requested as a deliverable item, should be included early in the development process. It does not take a larger organization or additional resources necessarily to accelerate the transition to production. However, the timing of when the resources are deployed is important. There is much information produced during development; however, if it is difficult to access, if it will slow down the process unless a plan exists.

Manufacturing Planning

This research was significant in that it examined multiple factors associated with product development and the multidisciplined organization roles needed to effect change to accelerate transition to production and manufacturing. One of the most significant aspects learned from the research is that more manufacturing readiness artifacts and objects may be necessary to produce or manufacture products than there are design documentation or objects in the Technical Data Package produced by the Design Engineering Team. As such, an extensive amount of planning and resource assignments are needed to execute the production of that information to enable development of the first prototypes in a factory. Therefore, a good Manufacturing Plan is needed to direct and

manage all of the aspects of preparing for the transition to production. It must start early in the development process prior to completion of the design.

Organization Structure Enabling Parallel Manufacturing Maturation with Product Development

The model in the research identified multiple roles significant in achieving manufacturing maturity and MRL values needed to assure meeting manufacturing production goals. It is shown that not only are such roles needed at the production phase, but they are needed during development phases in the Engineering Labs early in the process. Managing the Transition to Production during development required the participation of these multiple roles in an organized and efficient manner. For the industrial base to survive as viable businesses for their stakeholders, there is motivation to quickly recuperate development investments to be profitable. It may not be obvious though that the financial risk of the delay in the transition to production because of the lack of manufacturing readiness puts this at jeopardy. As such, perhaps this research can help those in the acquisition process understand that investments in the organization structure needed to support the acceleration of the transition to production will enable the more rapid deployment of critical solutions needed. This may not be appropriate for all projects. However, where acceleration of a solution is imperative, the model developed and advanced by this research can be used to justify any additional funding in this area. With some upfront investment in Manufacturing Readiness Acceleration, the overall period of performance needed to get systems into use will potentially result it cost savings and earlier deployment of the solution.

Information Flow for Influencing Manufacturing Readiness Acceleration

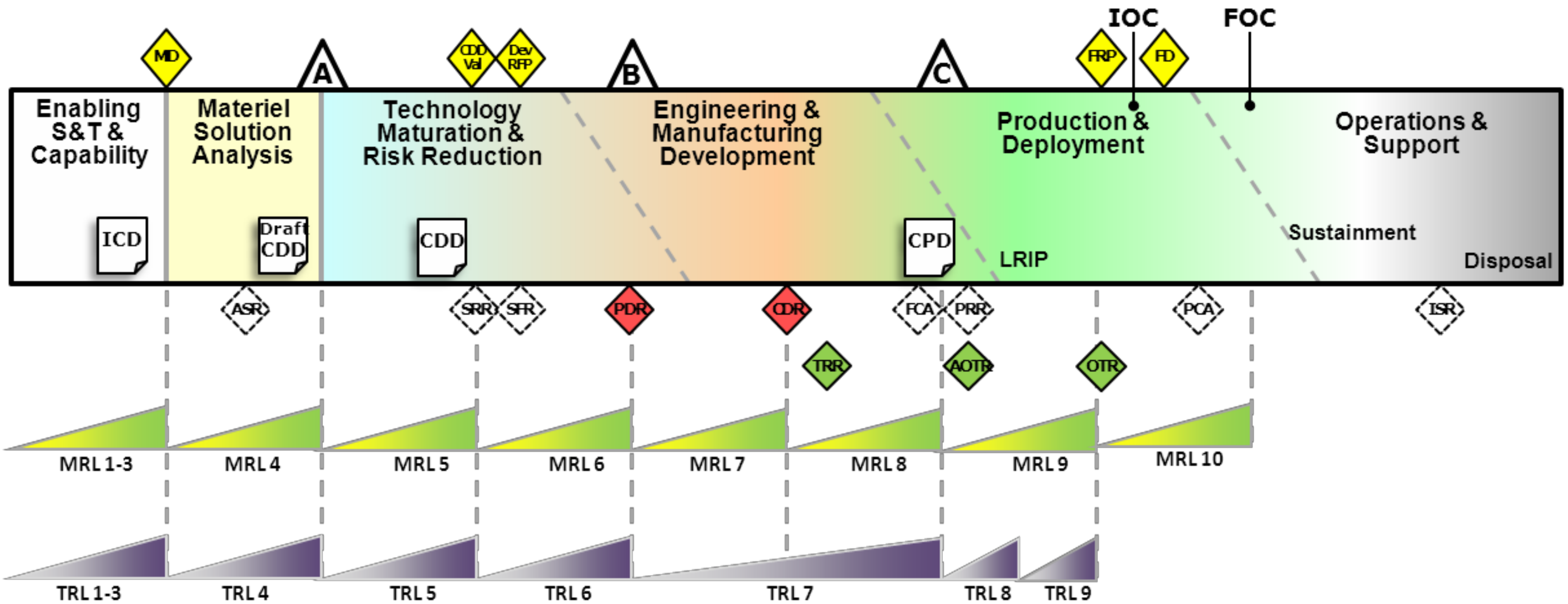
When it comes to the overall processes of an organization and its associated information flow, there needs to be a broad systematic approach to the design of the database system with the understanding of the overall value stream of the business processes of the organization. This is also the case for influencing the acceleration of manufacturing readiness. An individual project team may be able to produce all of the artifacts and information needed for the assessments that will occur at key milestone events; however, individual teams cannot usually affect the overall information system used by an enterprise. As such, this research provides a useful model for those involved in developing the enterprise level information systems of an organization. Because the information flow crosses many different functions, it is difficult for any single functional area to influence the whole system. The use of Model Based System Engineering and its multiple disciplined approach enables bringing all stakeholders into the process to understand the key interfaces.

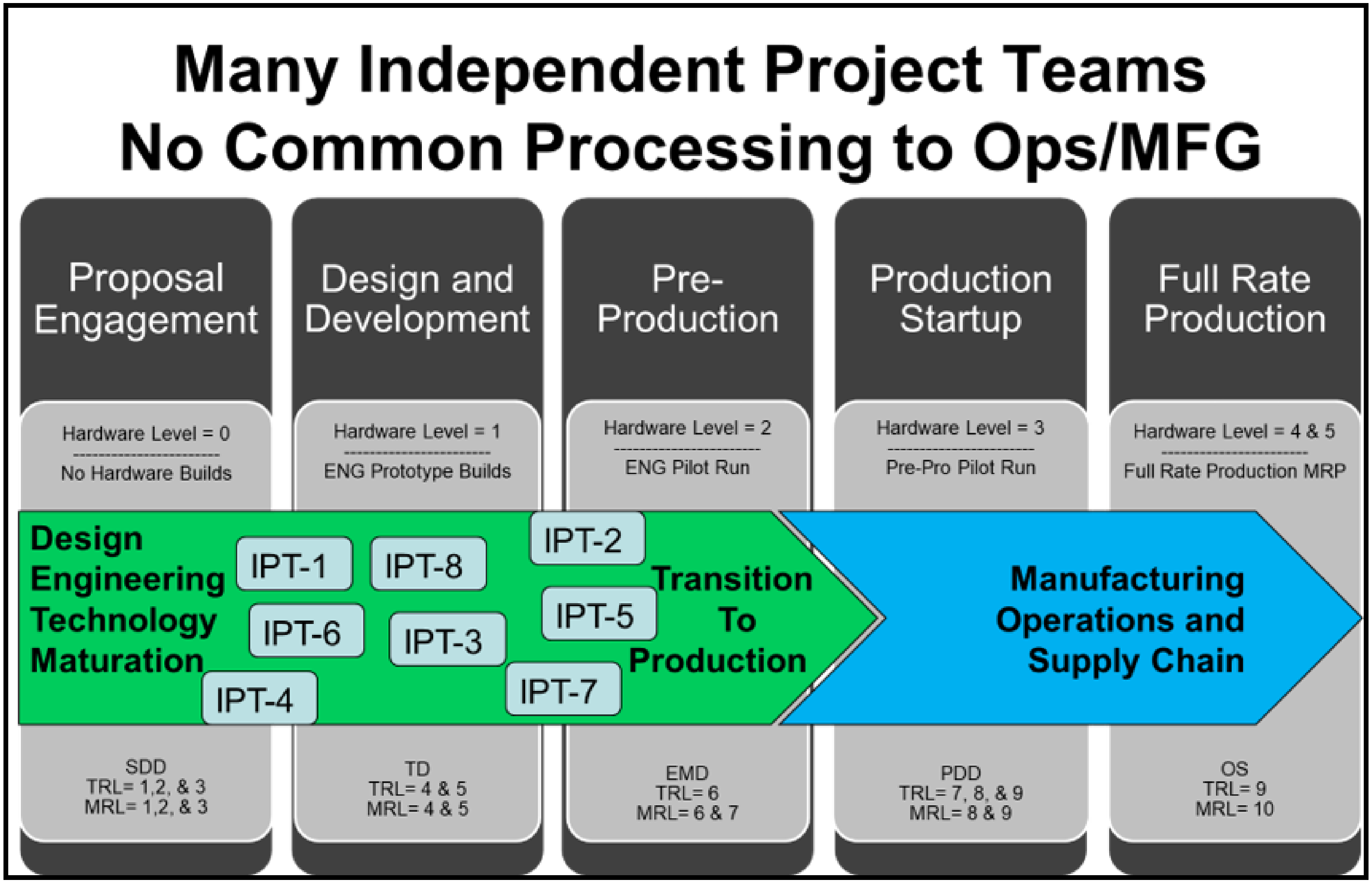
Research Impact Conclusion

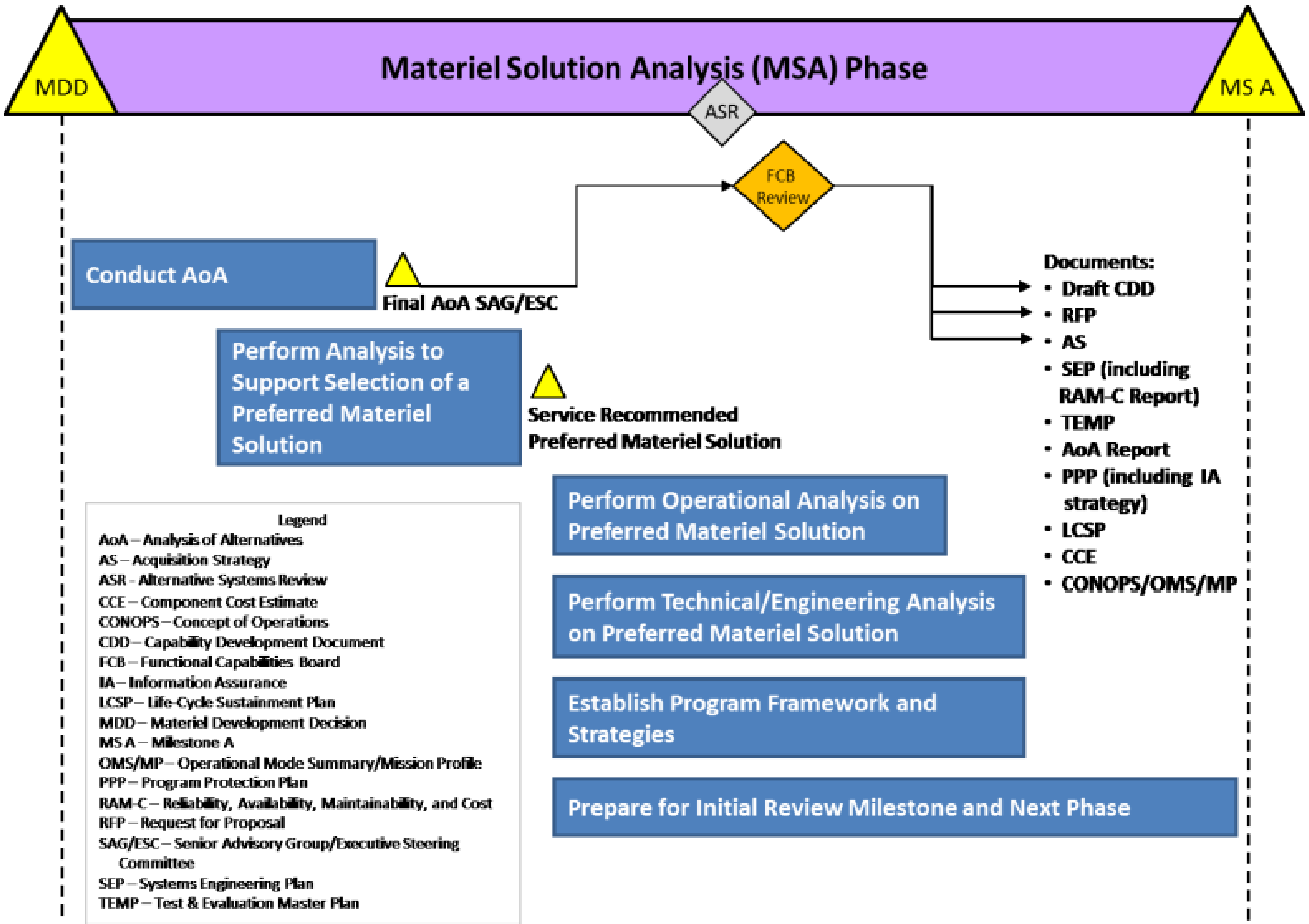
The investment to review an organization's development processes, organization structure, and process information flow to enable accelerating the transition to production are not insignificant. This research shows that there is merit in doing so, and establishing such systematic methodology can enable the establishment of a system which leverages work already being done to deliver more value for the investment. This investment may

lead to shorter development cycles to production and reduce redundant resources, which can then be applied to other critical projects and demands.

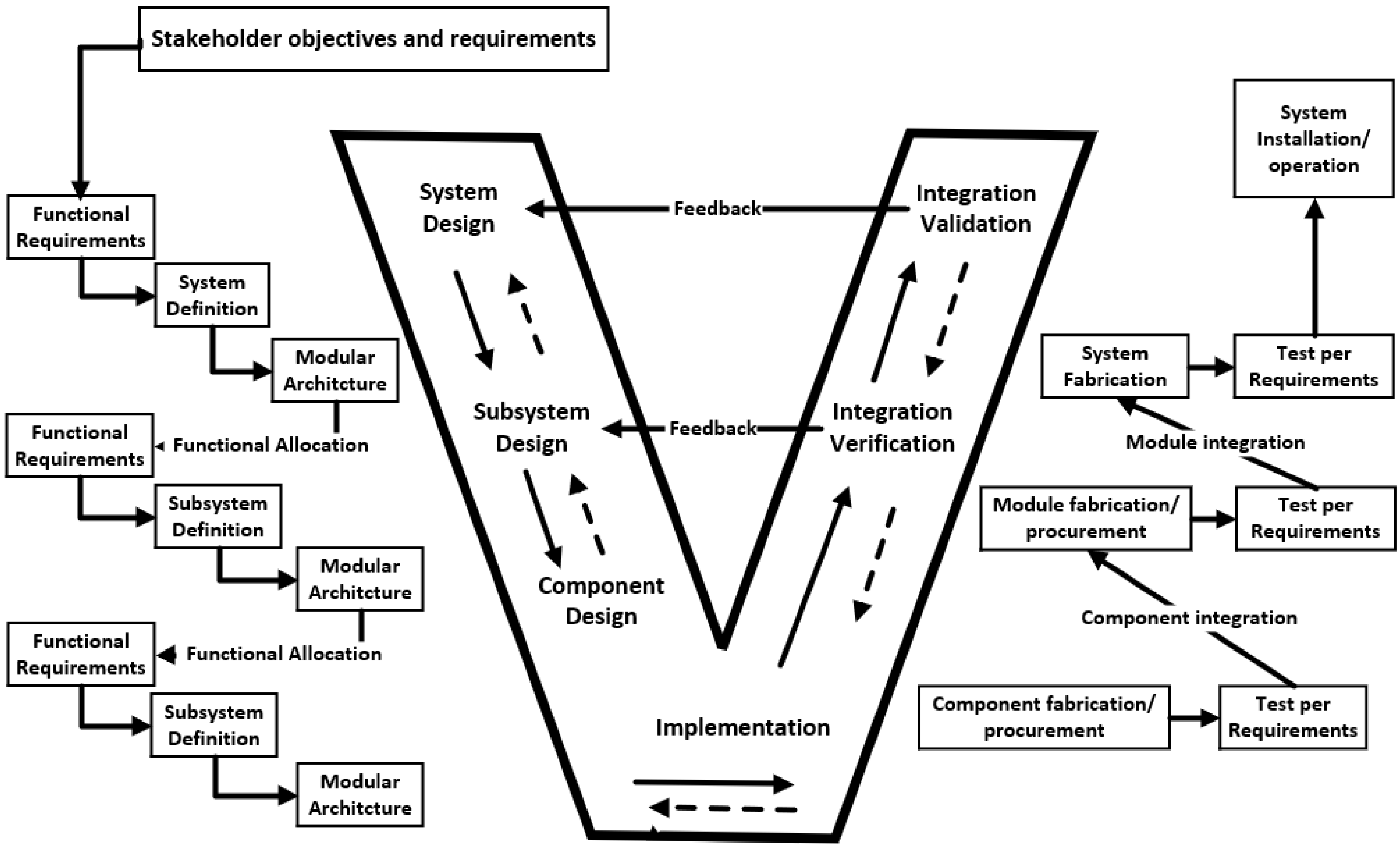
Appendix A: Key Figures in Landscape Layout for Readability

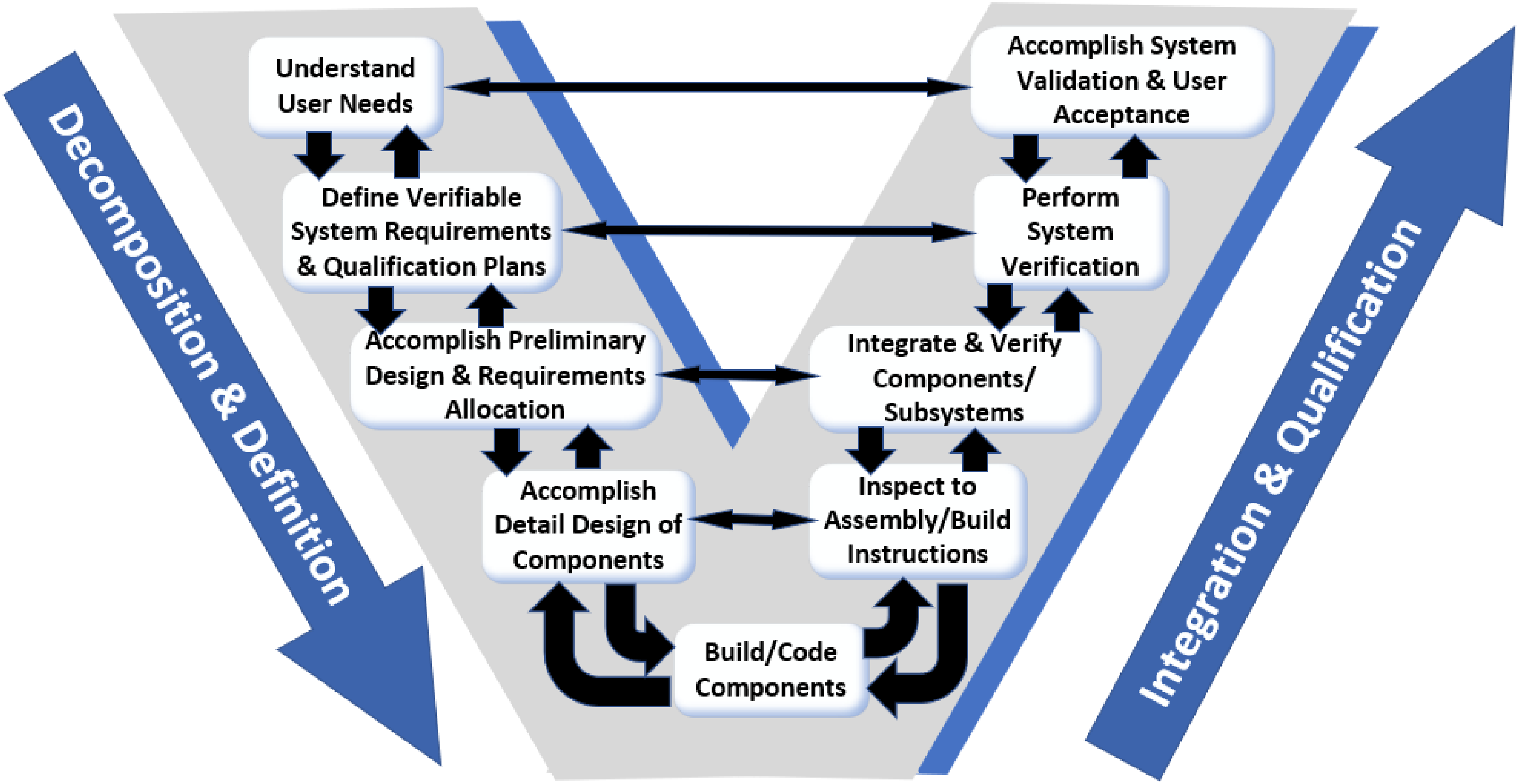



Many Independent Project Teams
No Common Processing to Ops/MFG
Proposal Engagement
Design and Development
Pre-Production
Production Startup
Full Rate Production
Hardware Level = 0
No Hardware Builds
Hardware Level = 1
ENG Prototype Builds
Hardware Level = 2
ENG Pilot Run
Hardware Level = 3
Pre-Pro Pilot Run
Hardware Level = 4 & 5
Full Rate Production MRP
Design Engineering Technology Maturation
IPT-1
IPT-8
IPT-2
IPT-6
IPT-3
IPT-5
IPT-4
IPT-7
Transition To Production
Manufacturing Operations and Supply Chain
SDD
TRL= 1,2, & 3
MRL= 1,2, & 3
TD
TRL= 4 & 5
MRL= 4 & 5
EMD
TRL= 6
MRL= 6 & 7
PDD
TRL= 7, 8, & 9
MRL= 8 & 9
OS
TRL= 9
MRL= 10

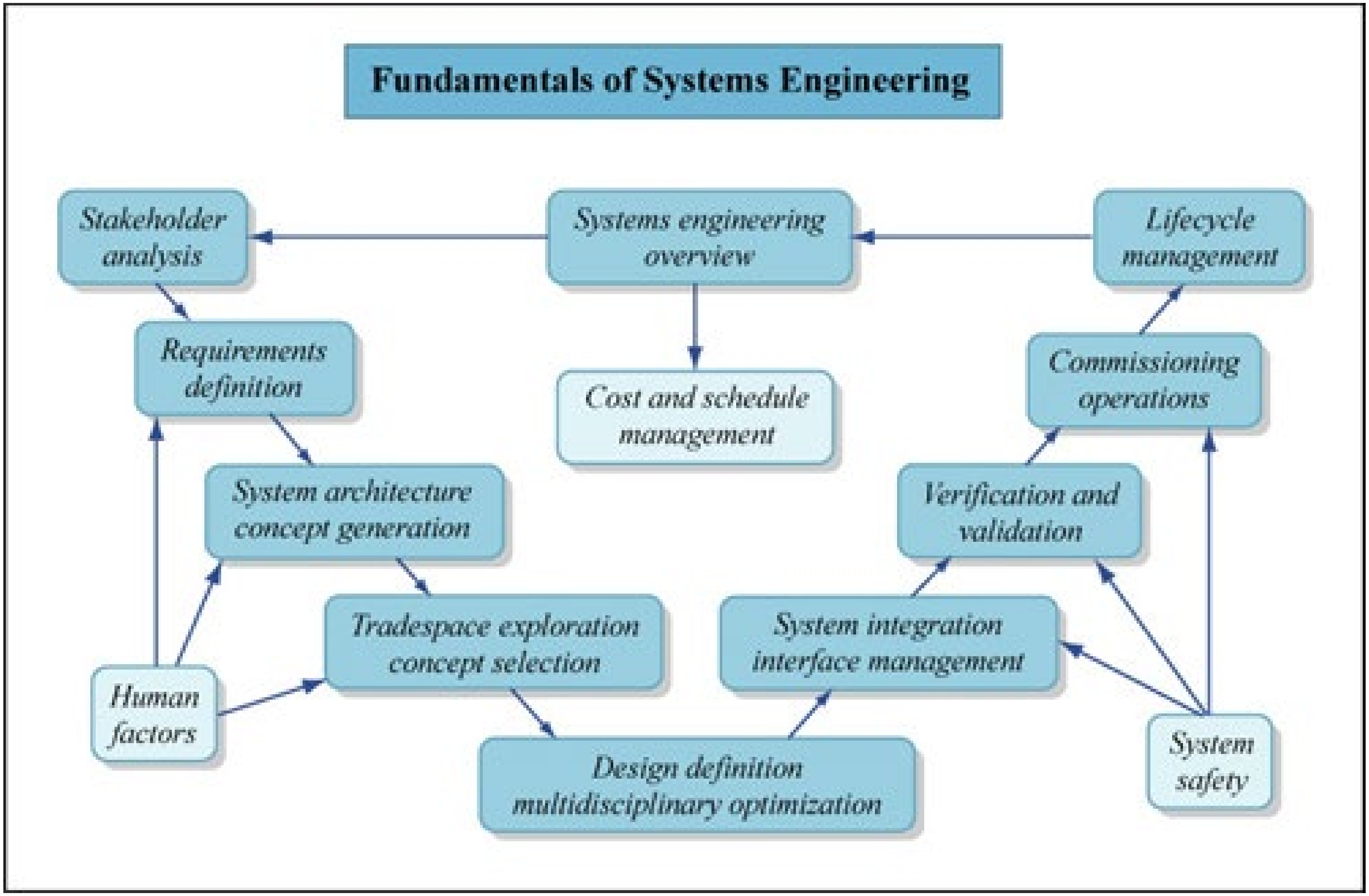


MDD
Materiel Solution Analysis (MSA) Phase
MS A
ASR
FCB Review
Conduct AoA
Final AoA SAG/ESC
Perform Analysis to Support Selection of a Preferred Materiel Solution
Service Recommended Preferred Materiel Solution
Documents:
• Draft CDD
• RFP
• AS
• SEP (including RAM-C Report)
• TEMP
• AoA Report
• PPP (including IA strategy)
• LCSP
• CCE
• CONOPS/OMS/MP
Perform Operational Analysis on Preferred Materiel Solution
Perform Technical/Engineering Analysis on Preferred Materiel Solution
Establish Program Framework and Strategies
Prepare for Initial Review Milestone and Next Phase
Legend
AoA – Analysis of Alternatives
AS – Acquisition Strategy
ASR - Alternative Systems Review
CCE – Component Cost Estimate
CONOPS – Concept of Operations
CDD – Capability Development Document
FCB – Functional Capabilities Board
IA – Information Assurance
LCSP – Life-Cycle Sustainment Plan
MDD – Materiel Development Decision
MS A – Milestone A
OMS/MP – Operational Mode Summary/Mission Profile
PPP – Program Protection Plan
RAM-C – Reliability, Availability, Maintainability, and Cost
RFP – Request for Proposal
SAG/ESC – Senior Advisory Group/Executive Steering Committee
SEP – Systems Engineering Plan
TEMP – Test & Evaluation Master Plan

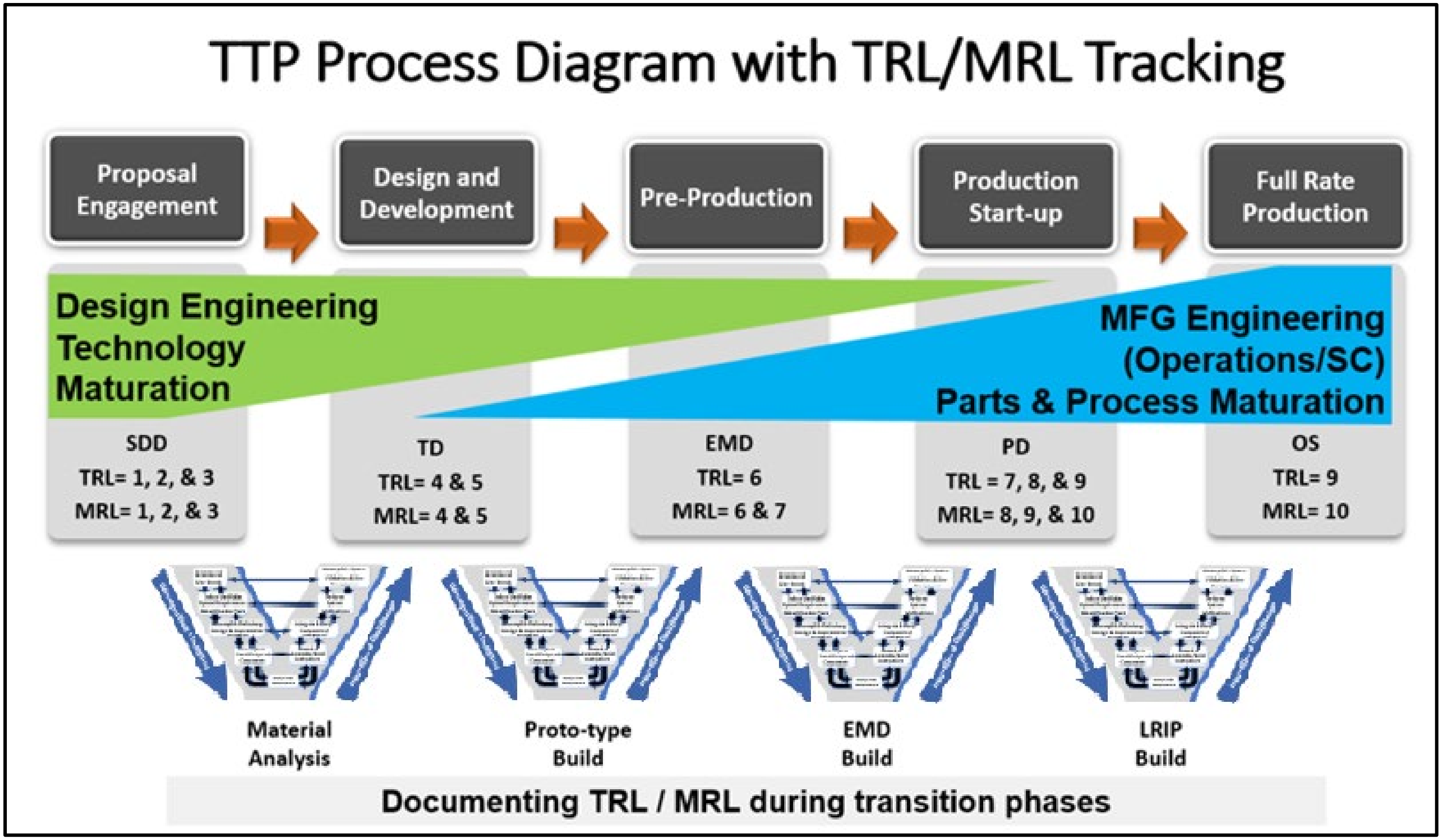

Stakeholder objectives and requirements
Functional Requirements
System Definition
Modular Architcture
Functional Allocation
Functional Requirements
Subsystem Definition
Modular Architcture
Functional Allocation
Functional Requirements
Subsystem Definition
Modular Architcture
System Design
Feedback
Integration Validation
Subsystem Design
Feedback
Integration Verification
Component Design
Implementation
System Installation/ operation
System Fabrication
Test per Requirements
Module integration
Module fabrication/ procurement
Test per Requirements
Component integration
Component fabrication/ procurement
Test per Requirements



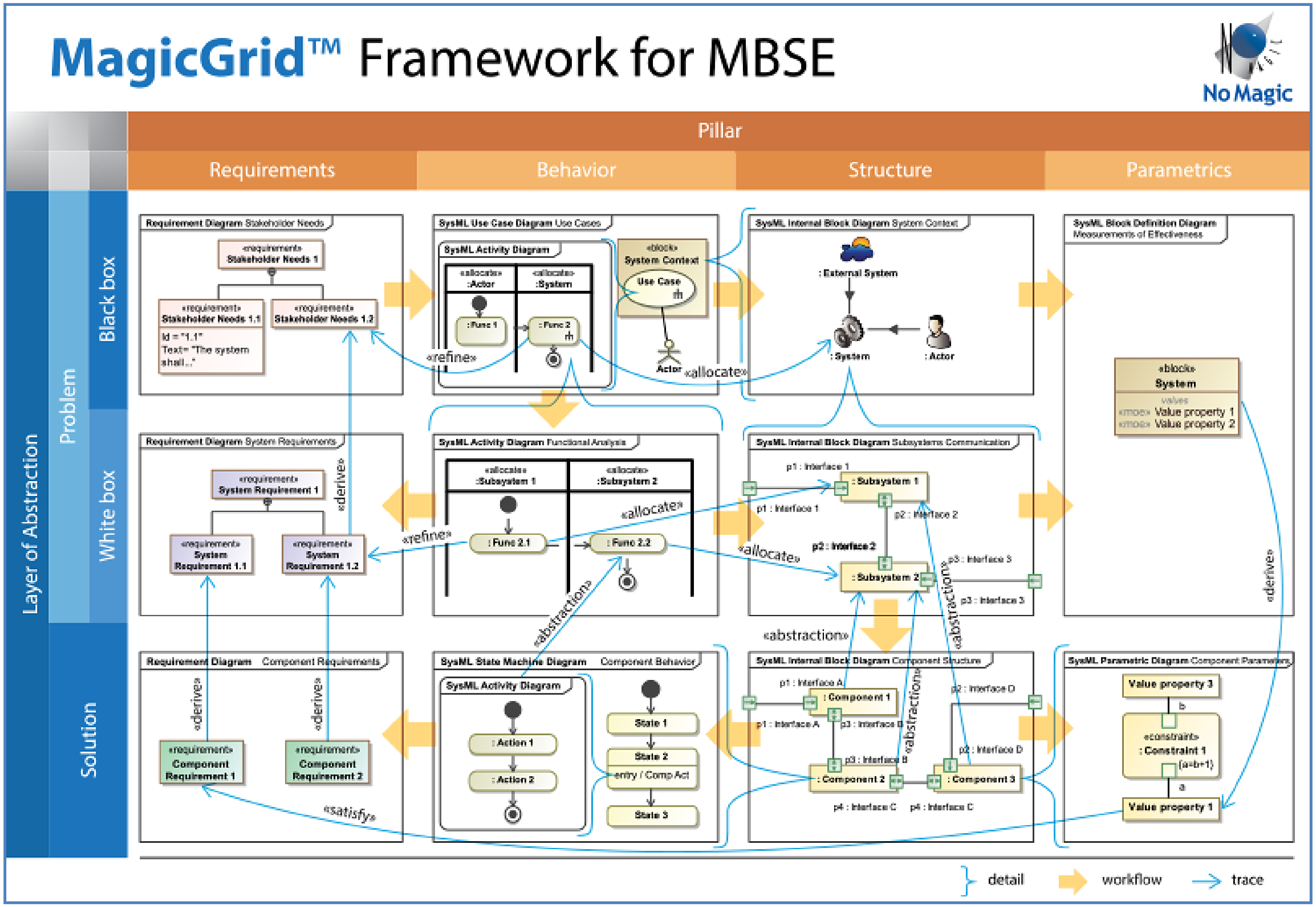
Decomposition & Definition
Understand User Needs
Define Verifiable System Requirements & Qualification Plans
Accomplish Preliminary Design & Requirements Allocation
Accomplish Detail Design of Components
Build/Code Components
Inspect to Assembly/Build Instructions
Integrate & Verify Components/ Subsystems
Perform System Verification
Accomplish System Validation & User Acceptance
Integration & Qualification



Fundamentals of Systems Engineering
Stakeholder analysis
Systems engineering overview
Lifecycle management
Requirements definition
Cost and schedule management
Commissioning operations
System architecture concept generation
Verification and validation
Tradespace exploration concept selection
System integration interface management
Human factors
System safety
Design definition multidisciplinary optimization



TTP Process Diagram with TRL/MRL Tracking
Proposal Engagement
Design and Development
Pre-Production
Production Start-up
Full Rate Production
Design Engineering Technology Maturation
MFG Engineering (Operations/SC) Parts & Process Maturation
SDD
TRL= 1, 2, & 3
MRL= 1, 2, & 3
TD
TRL= 4 & 5
MRL= 4 & 5
EMD
TRL= 6
MRL= 6 & 7
PD
TRL = 7, 8, & 9
MRL= 8, 9, & 10
OS
TRL= 9
MRL= 10
Material Analysis
Proto-type Build
EMD Build
LRIP Build
Documenting TRL / MRL during transition phases



https://www.nomagic.com/support/quick-reference-guides)

Why: Protect and Support Warfighter, Customer's Mission, and Company Shareholder Investments

Who: Program Management	Contracts, Funding, Company Resources

↓

What: Product Deliverables per Technical Data Package (TDP) and Contract Quality Requirements (CQR)

Who: Engineering/ Mission Assurance	TDP & CQR

↓

How, Where, When: Manufacturing Plan including Key Direction and Conversion of EDP to MFG Instructions

Who: Program Operations	Manufacturing Plan

↓

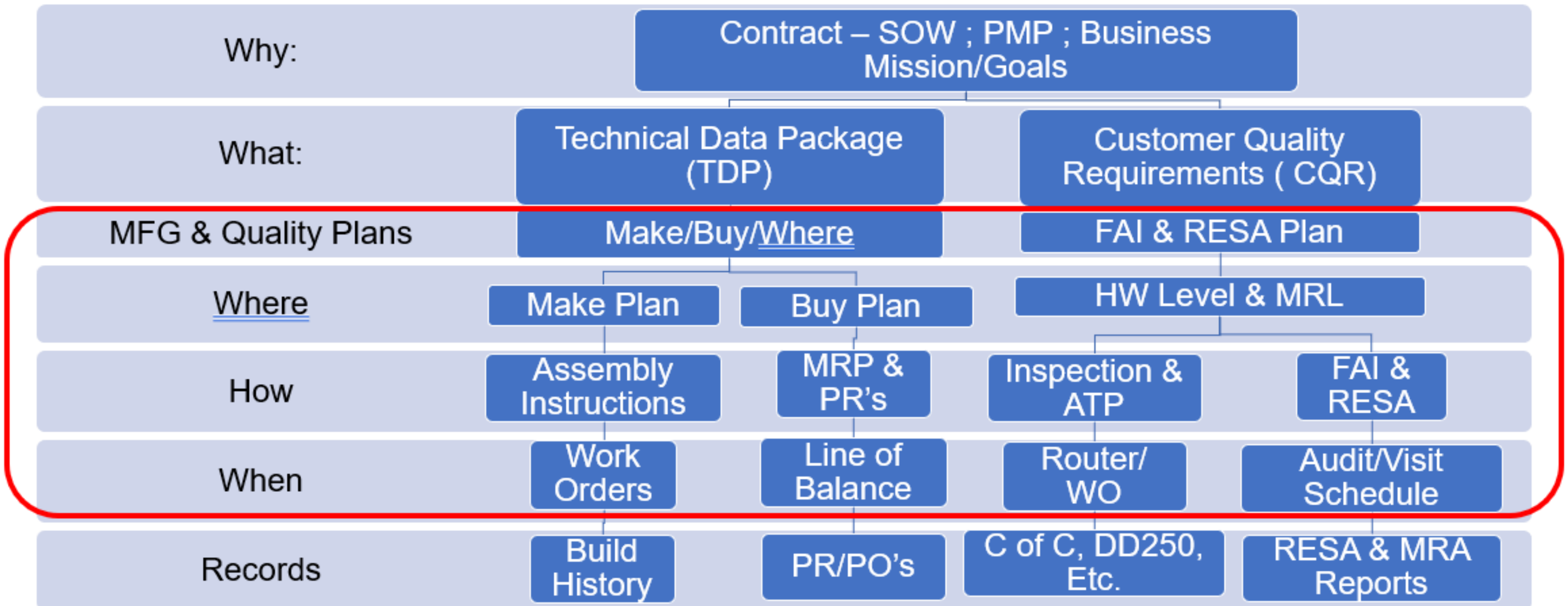
TDP Converted to MFG Processes/Documents (AI's, TP's, Work Orders, Purchase Requisitions & Purchase Orders)

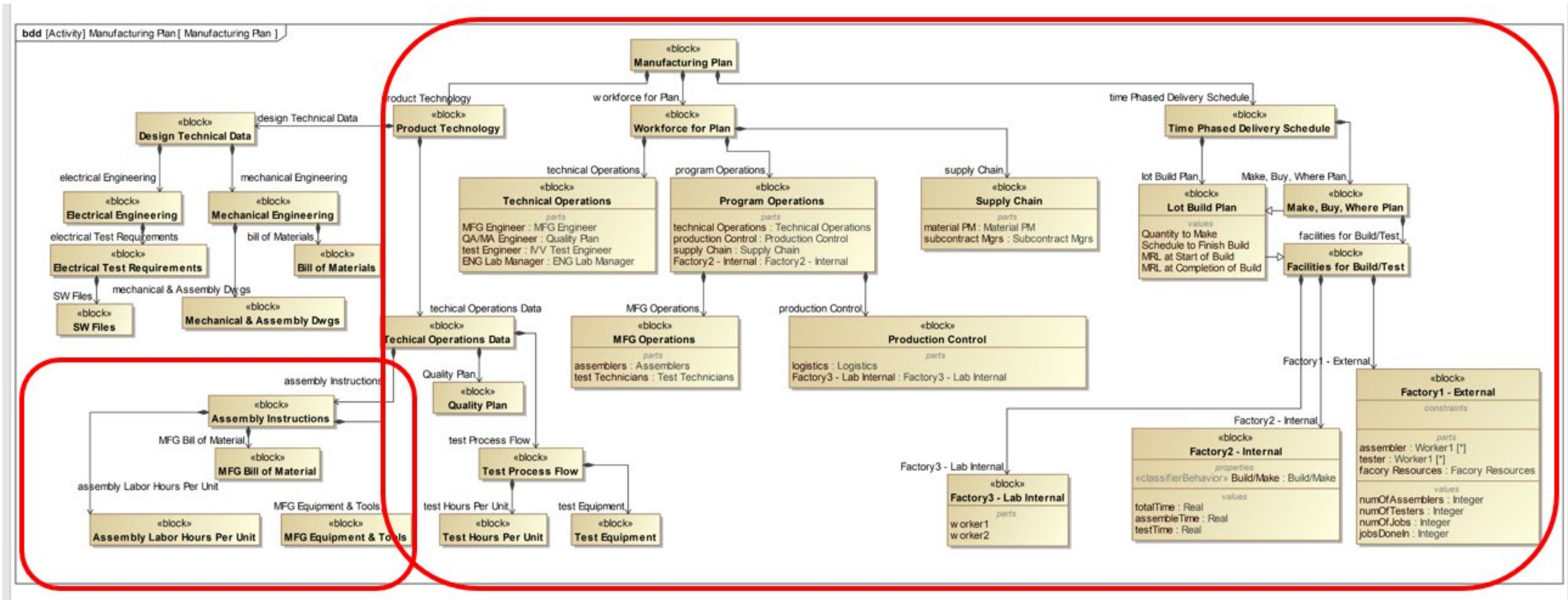
Who: MFG Eng, Test Eng, Production Control	AI's, TP's, Master Schedule, WO's, PR's, PO's

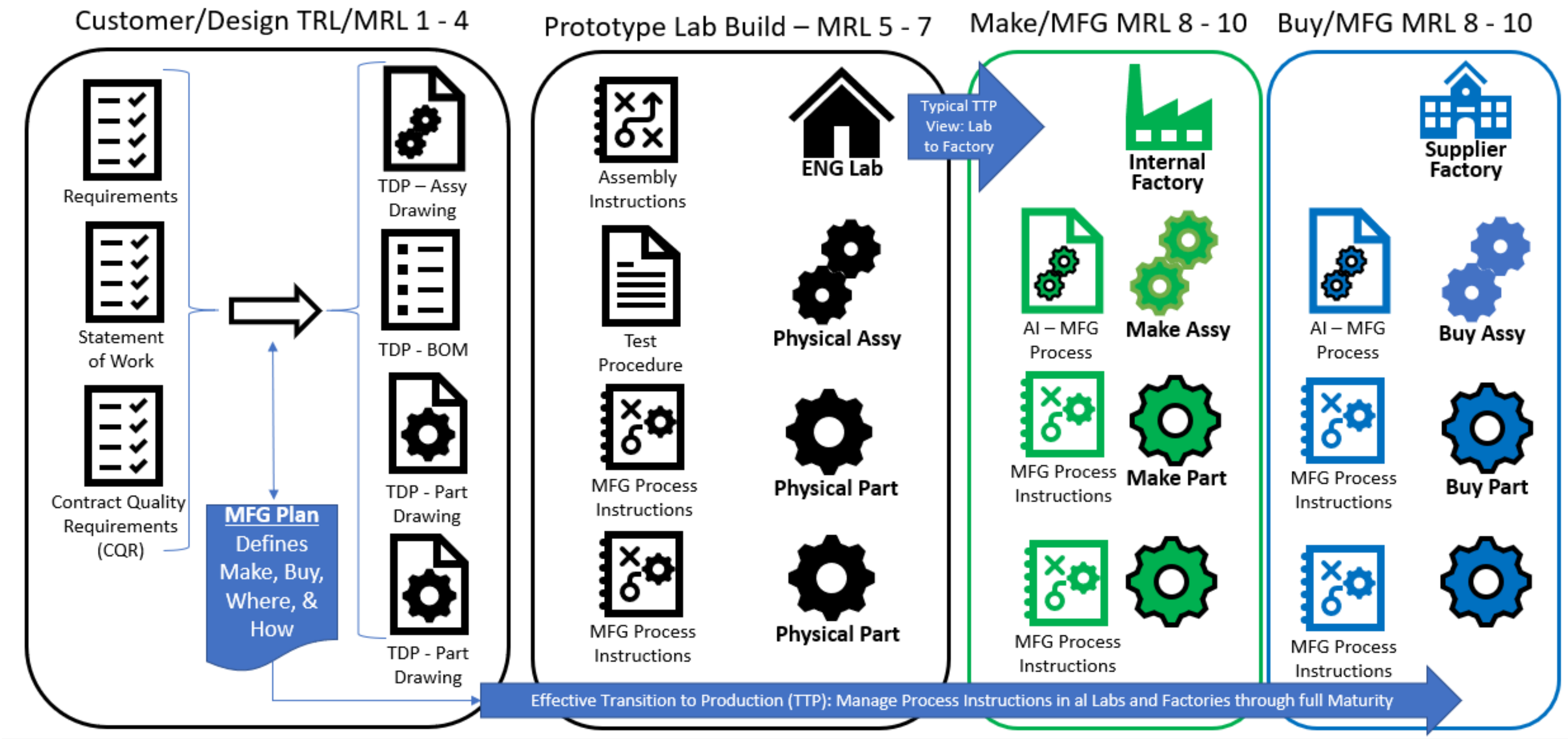
↓

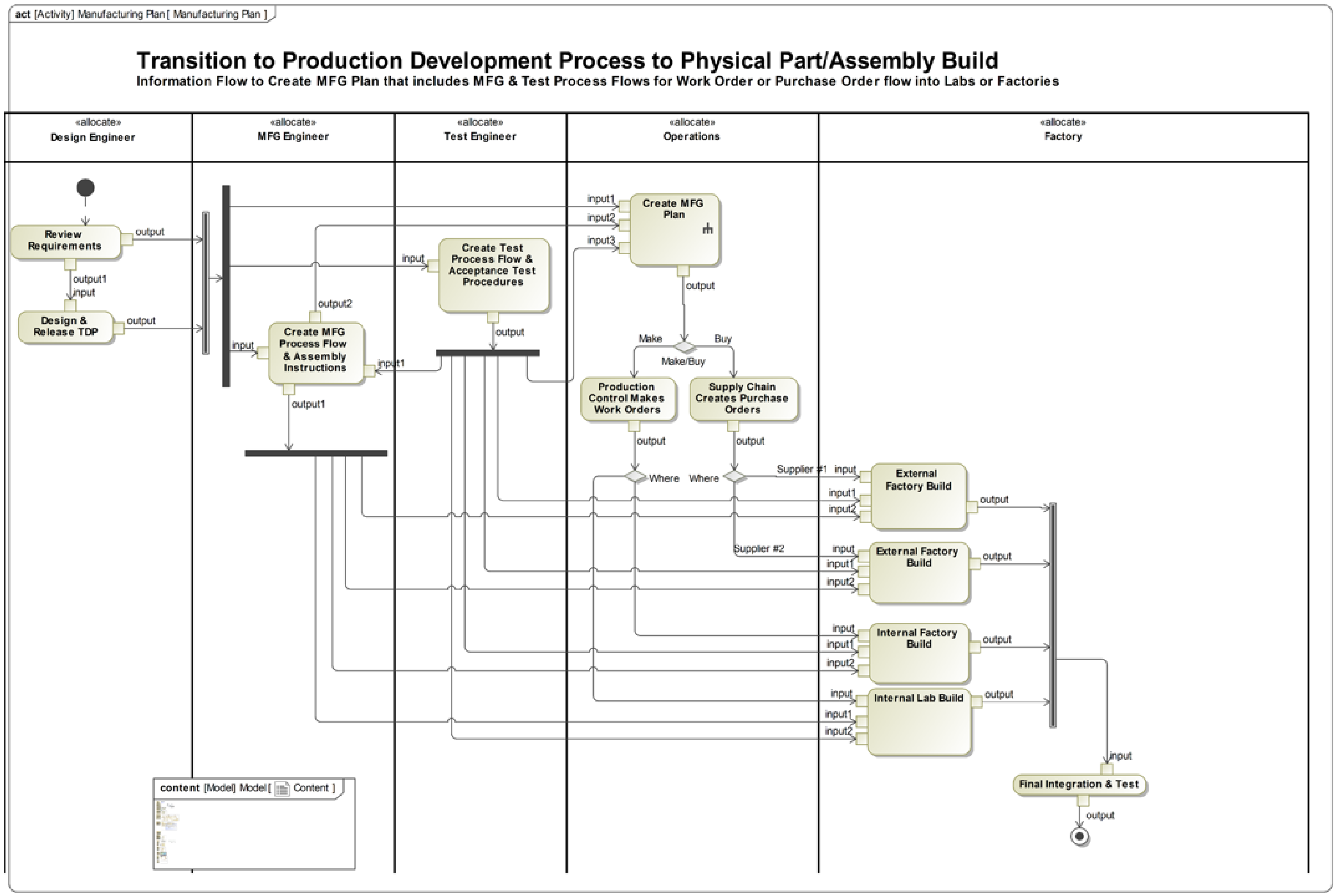
Execution: Mfg Plan executed by all functions and monitored by Program Operations

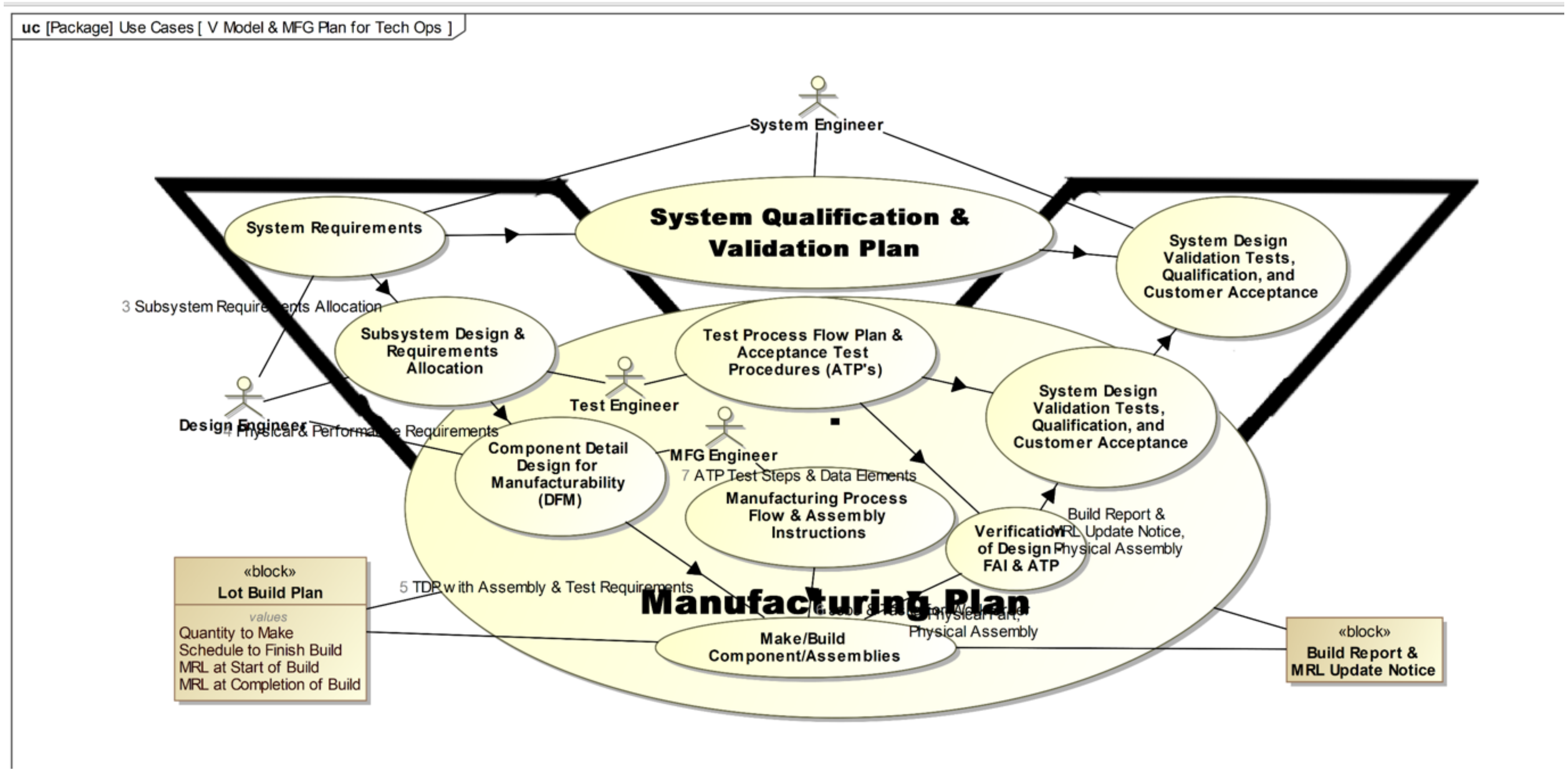
Who: MFG Ops, Sub-Contractors, Suppliers	Line of Balance Monitoring/Execution, Completion & Sell-off

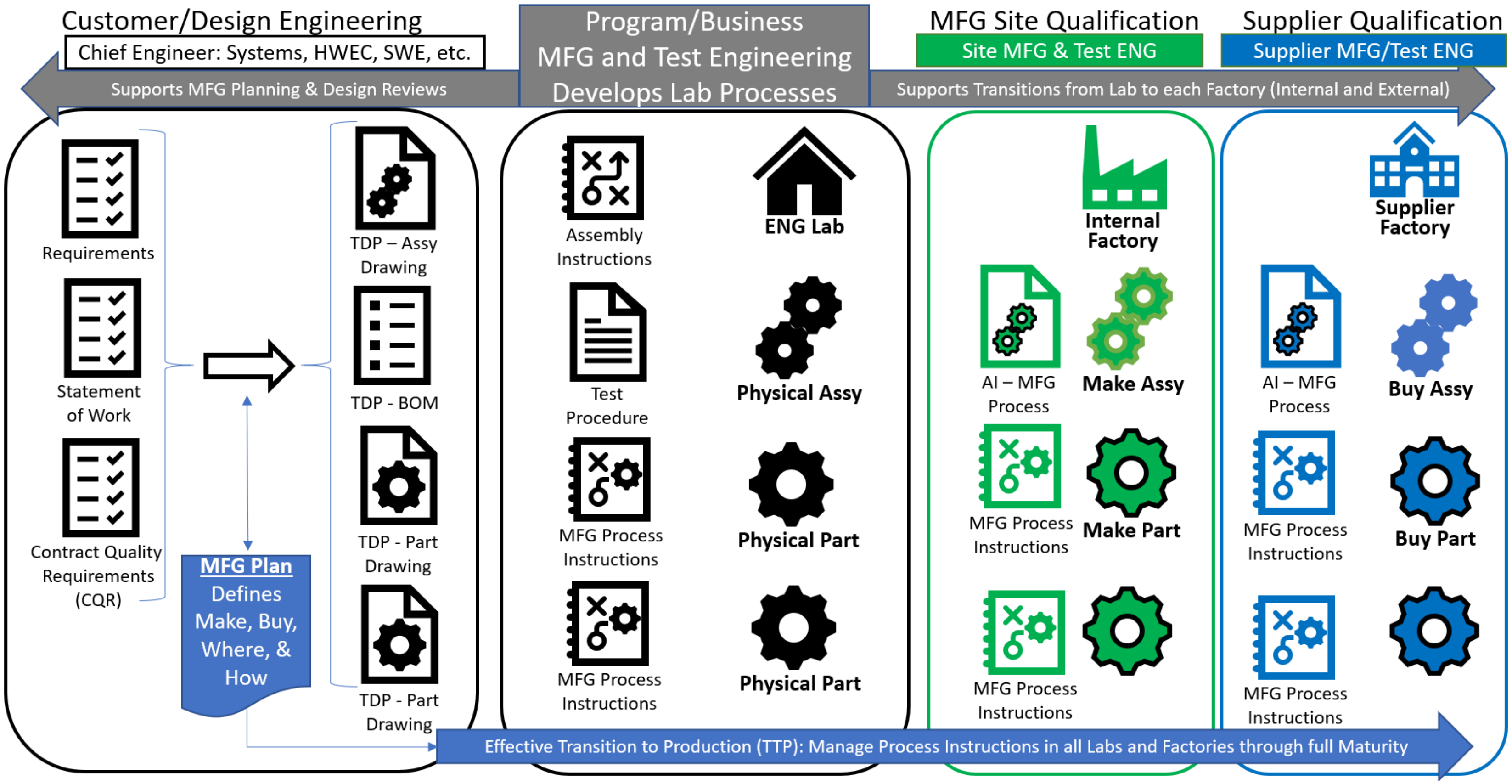

Why:
Contract – SOW ; PMP ; Business Mission/Goals
What:
Technical Data Package (TDP)
Customer Quality Requirements (CQR)
MFG & Quality Plans
Make/Buy/Where
FAI & RESA Plan
Where
Make Plan
Buy Plan
HW Level & MRL
How
Assembly Instructions
MRP & PR's
Inspection & ATP
FAI & RESA
When
Work Orders
Line of Balance
Router/ WO
Audit/Visit Schedule
Records
Build History
PR/PO's
C of C, DD250, Etc.
RESA & MRA Reports


bdd [Activity] Manufacturing Plan [Manufacturing Plan]
«block» Manufacturing Plan
roduct Technology
workforce for Plan
time Phased Delivery Schedule
«block» Design Technical Data
design Technical Data
«block» Product Technology
«block» Workforce for Plan
«block» Time Phased Delivery Schedule
electrical Engineering
mechanical Engineering
technical Operations
program Operations
supply Chain
lot Build Plan
Make, Buy, Where Plan
«block» Electrical Engineering
«block» Mechanical Engineering
«block» Technical Operations
parts
MFG Engineer : MFG Engineer
QA/MA Engineer : Quality Plan
test Engineer : IVV Test Engineer
ENG Lab Manager : ENG Lab Manager
«block» Program Operations
parts
technical Operations : Technical Operations
production Control : Production Control
supply Chain : Supply Chain
Factory2 - Internal : Factory2 - Internal
«block» Supply Chain
parts
material PM : Material PM
subcontract Mgrs : Subcontract Mgrs
«block» Lot Build Plan
values
Quantity to Make
Schedule to Finish Build
MRL at Start of Build
MRL at Completion of Build
«block» Make, Buy, Where Plan
facilities for Build/Test
«block» Facilities for Build/Test
electrical Test Requirements
bill of Materials
«block» Electrical Test Requirements
«block» Bill of Materials
SW Files
mechanical & Assembly Dwgs
«block» SW Files
«block» Mechanical & Assembly Dwgs
techical Operations Data
MFG Operations
production Control
«block» Techical Operations Data
«block» MFG Operations
parts
assemblers : Assemblers
test Technicians : Test Technicians
«block» Production Control
parts
logistics : Logistics
Factory3 - Lab Internal : Factory3 - Lab Internal
assembly Instructions
Quality Plan
«block» Quality Plan
Factory1 - External
«block» Assembly Instructions
«block» Factory1 - External
constraints
parts
assembler : Worker1 [*]
tester : Worker1 [*]
facory Resources : Facory Resources
values
numOfAssemblers : Integer
numOfTesters : Integer
numOfJobs : Integer
jobsDoneIn : Integer
MFG Bill of Material
test Process Flow
Factory2 - Internal
«block» MFG Bill of Material
«block» Test Process Flow
«block» Factory2 - Internal
properties
«classifierBehavior» Build/Make : Build/Make
values
totalTime : Real
assembleTime : Real
testTime : Real
assembly Labor Hours Per Unit
Factory3 - Lab Internal
«block» Factory3 - Lab Internal
parts
worker1
worker2
MFG Equipment & Tools
test Hours Per Unit
test Equipment
«block» Assembly Labor Hours Per Unit
«block» MFG Equipment & Tools
«block» Test Hours Per Unit
«block» Test Equipment

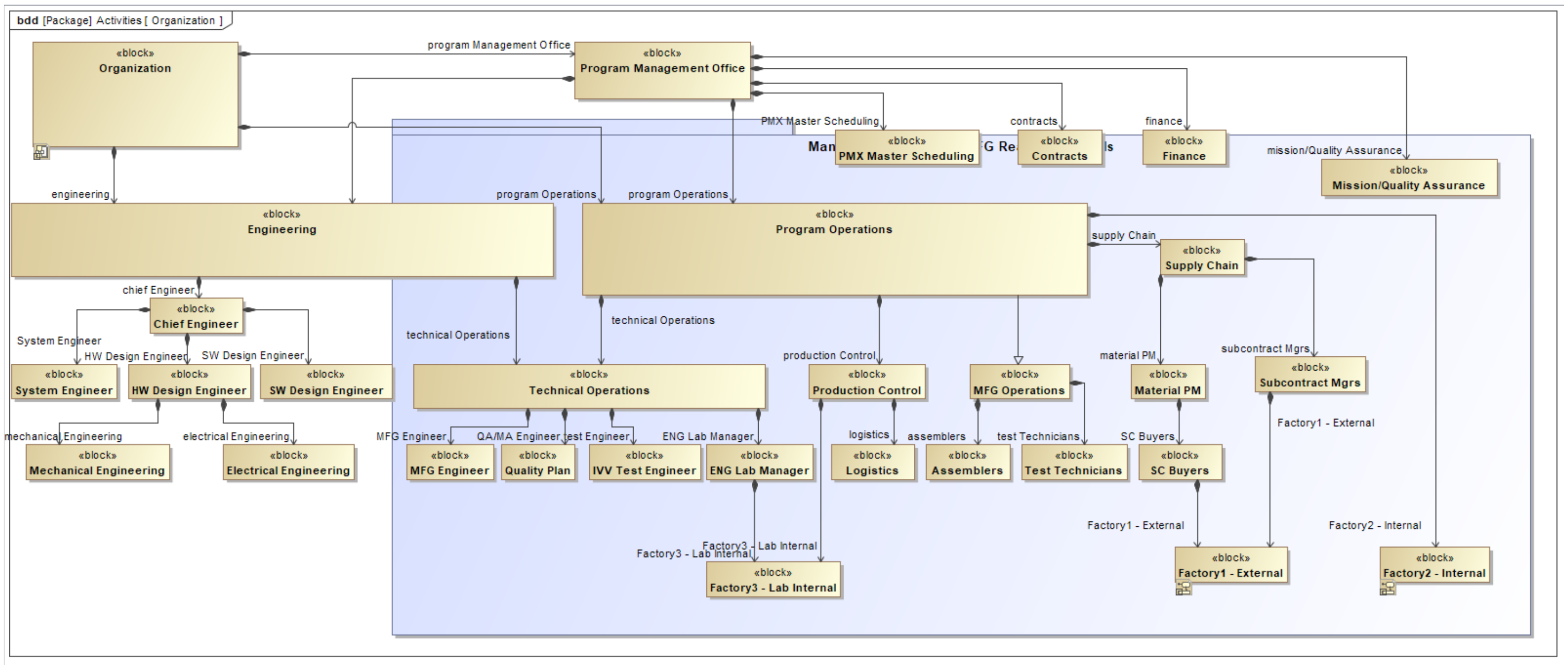

Customer/Design TRL/MRL 1 - 4
Prototype Lab Build – MRL 5 - 7
Make/MFG MRL 8 - 10
Buy/MFG MRL 8 - 10
Requirements
Statement of Work
Contract Quality Requirements (CQR)
MFG Plan
Defines Make, Buy, Where, & How
TDP – Assy Drawing
TDP - BOM
TDP - Part Drawing
TDP - Part Drawing
Assembly Instructions
Test Procedure
MFG Process Instructions
MFG Process Instructions
ENG Lab
Physical Assy
Physical Part
Physical Part
Typical TTP View: Lab to Factory
Internal Factory
AI – MFG Process
Make Assy
MFG Process Instructions
Make Part
MFG Process Instructions
Supplier Factory
AI – MFG Process
Buy Assy
MFG Process Instructions
Buy Part
MFG Process Instructions
Effective Transition to Production (TTP): Manage Process Instructions in al Labs and Factories through full Maturity

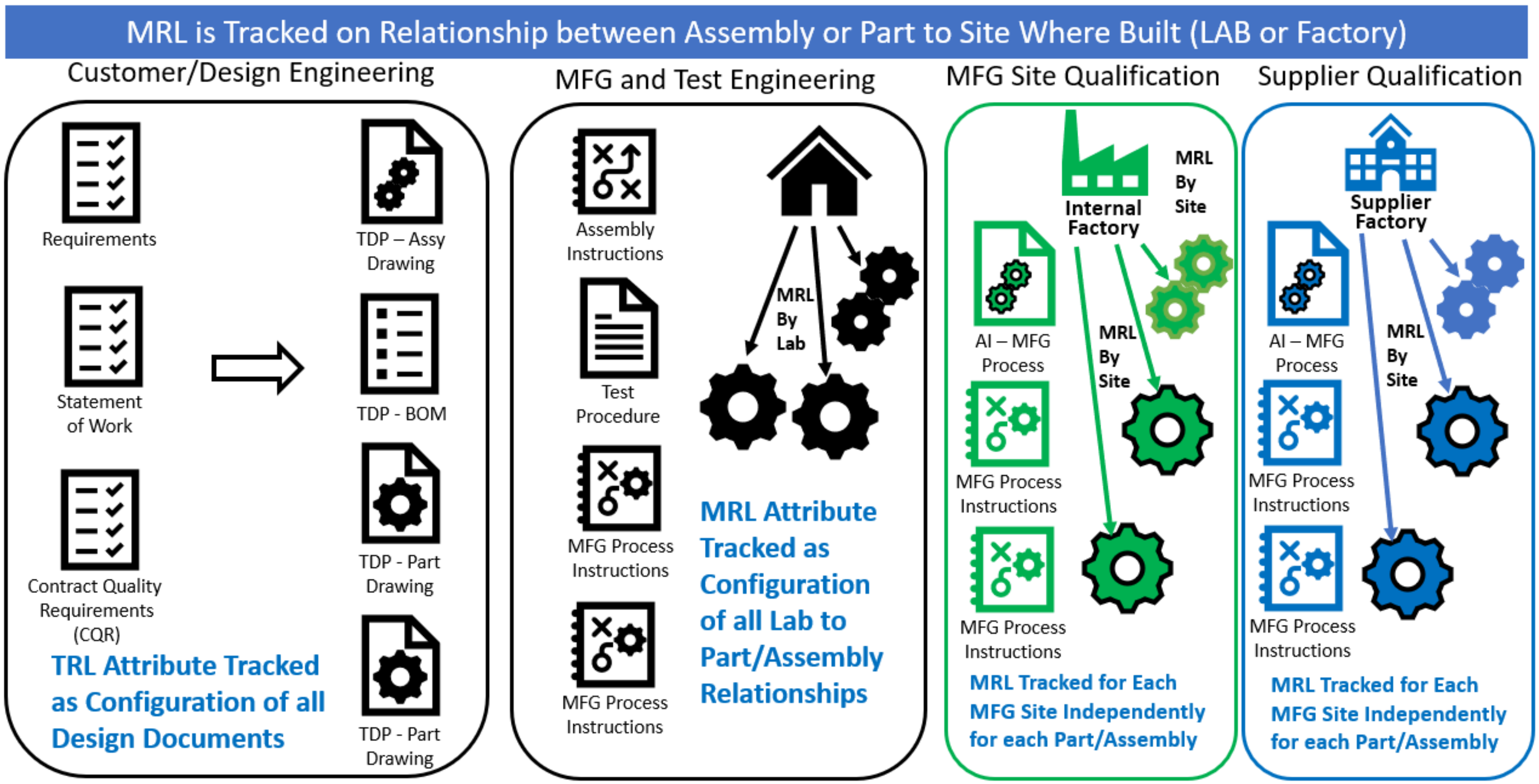

act [Activity] Manufacturing Plan [Manufacturing Plan]
Transition to Production Development Process to Physical Part/Assembly Build
Information Flow to Create MFG Plan that includes MFG & Test Process Flows for Work Order or Purchase Order flow into Labs or Factories
«allocate» Design Engineer
«allocate» MFG Engineer
«allocate» Test Engineer
«allocate» Operations
«allocate» Factory
Review Requirements
output
output1
input
Design & Release TDP
output
input
Create MFG Process Flow & Assembly Instructions
output2
output1
input1
Create Test Process Flow & Acceptance Test Procedures
input
output
Create MFG Plan
input1
input2
input3
output
Make
Buy
Make/Buy
Production Control Makes Work Orders
Supply Chain Creates Purchase Orders
output
output
Where
Where
Supplier #1
Supplier #2
External Factory Build
External Factory Build
Internal Factory Build
Internal Lab Build
input
input1
input2
output
Final Integration & Test
input
output
content [Model] Model [Content]

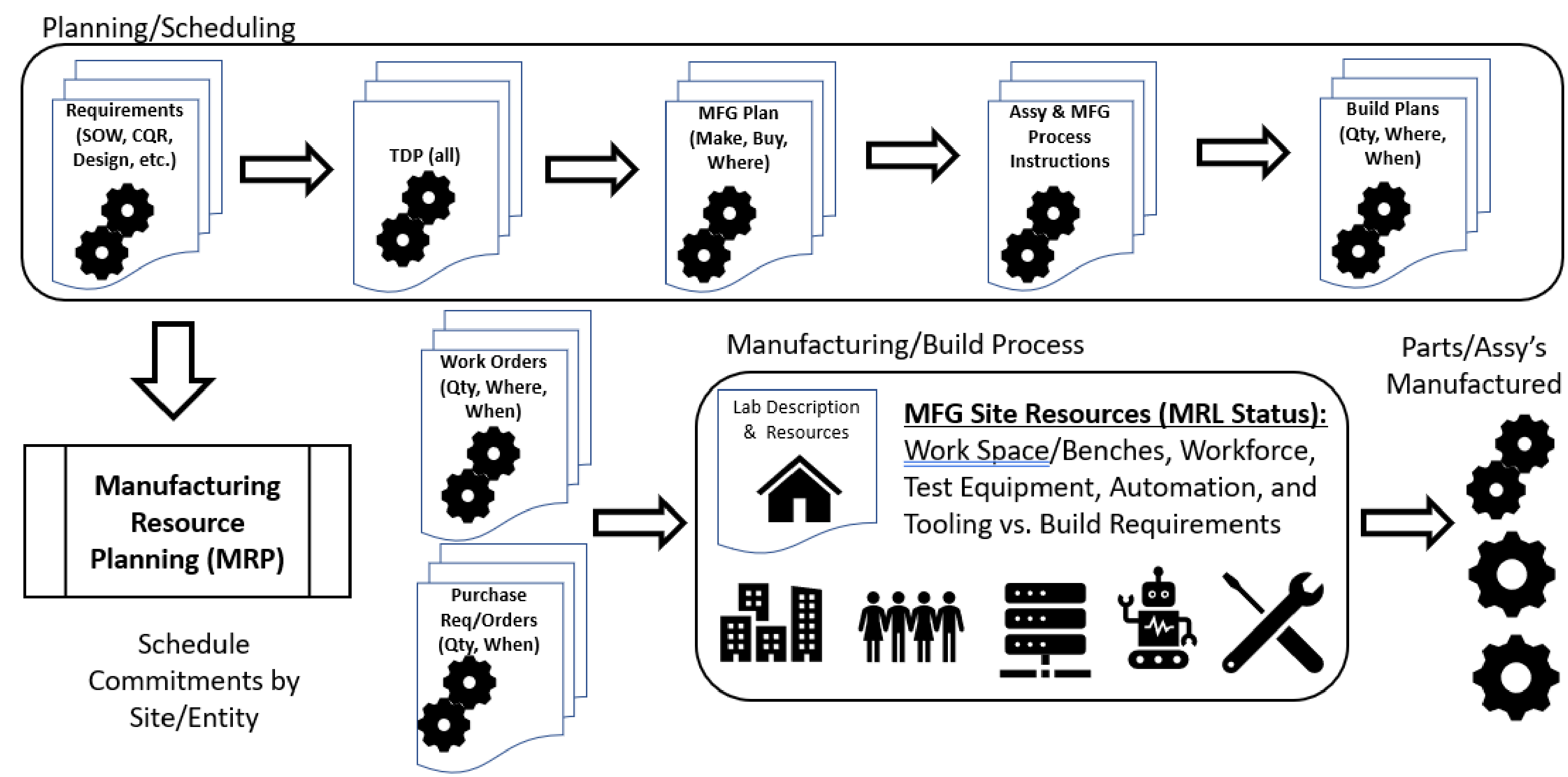

uc [Package] Use Cases [V Model & MFG Plan for Tech Ops]
System Engineer
System Requirements
System Qualification & Validation Plan
System Design Validation Tests, Qualification, and Customer Acceptance
3 Subsystem Requirements Allocation
Subsystem Design & Requirements Allocation
Test Process Flow Plan & Acceptance Test Procedures (ATP's)
Test Engineer
Design Engineer
4 Physical & Performance Requirements
MFG Engineer
Component Detail Design for Manufacturability (DFM)
7 ATP Test Steps & Data Elements
Manufacturing Process Flow & Assembly Instructions
System Design Validation Tests, Qualification, and Customer Acceptance
Verification of Design FAI & ATP
Build Report & MRL Update Notice, Physical Assembly
«block»
Lot Build Plan
values
Quantity to Make
Schedule to Finish Build
MRL at Start of Build
MRL at Completion of Build
5 TDP with Assembly & Test Requirements
Manufacturing Plan
Physical Part, Physical Assembly
Make/Build Component/Assemblies
«block»
Build Report & MRL Update Notice



Customer/Design Engineering
Chief Engineer: Systems, HWEC, SWE, etc.
Supports MFG Planning & Design Reviews
Program/Business MFG and Test Engineering Develops Lab Processes
MFG Site Qualification
Site MFG & Test ENG
Supplier Qualification
Supplier MFG/Test ENG
Supports Transitions from Lab to each Factory (Internal and External)
Requirements
Statement of Work
Contract Quality Requirements (CQR)
MFG Plan Defines Make, Buy, Where, & How
TDP – Assy Drawing
TDP - BOM
TDP - Part Drawing
TDP - Part Drawing
Assembly Instructions
ENG Lab
Test Procedure
Physical Assy
MFG Process Instructions
Physical Part
MFG Process Instructions
Physical Part
Internal Factory
AI – MFG Process
Make Assy
MFG Process Instructions
Make Part
MFG Process Instructions
Supplier Factory
AI – MFG Process
Buy Assy
MFG Process Instructions
Buy Part
MFG Process Instructions
Effective Transition to Production (TTP): Manage Process Instructions in all Labs and Factories through full Maturity


bdd [Package] Activities [Organization]
«block» Organization
«block» Program Management Office
program Management Office
PMX Master Scheduling
«block» PMX Master Scheduling
contracts
«block» Contracts
finance
«block» Finance
mission/Quality Assurance
«block» Mission/Quality Assurance
engineering
«block» Engineering
program Operations
«block» Program Operations
supply Chain
«block» Supply Chain
chief Engineer
«block» Chief Engineer
System Engineer
HW Design Engineer
SW Design Engineer
«block» System Engineer
«block» HW Design Engineer
«block» SW Design Engineer
technical Operations
«block» Technical Operations
production Control
«block» Production Control
«block» MFG Operations
material PM
«block» Material PM
subcontract Mgrs
«block» Subcontract Mgrs
mechanical Engineering
electrical Engineering
«block» Mechanical Engineering
«block» Electrical Engineering
MFG Engineer
QA/MA Engineer
test Engineer
ENG Lab Manager
«block» MFG Engineer
«block» Quality Plan
«block» IVV Test Engineer
«block» ENG Lab Manager
logistics
assemblers
test Technicians
SC Buyers
«block» Logistics
«block» Assemblers
«block» Test Technicians
«block» SC Buyers
Factory1 - External
Factory2 - Internal
Factory3 - Lab Internal
«block» Factory3 - Lab Internal
«block» Factory1 - External
«block» Factory2 - Internal


MRL is Tracked on Relationship between Assembly or Part to Site Where Built (LAB or Factory)
Customer/Design Engineering
MFG and Test Engineering
MFG Site Qualification
Supplier Qualification
Requirements
TDP – Assy Drawing
Statement of Work
TDP - BOM
Contract Quality Requirements (CQR)
TDP - Part Drawing
TRL Attribute Tracked as Configuration of all Design Documents
TDP - Part Drawing
Assembly Instructions
Test Procedure
MFG Process Instructions
MFG Process Instructions
MRL By Lab
MRL Attribute Tracked as Configuration of all Lab to Part/Assembly Relationships
Internal Factory
MRL By Site
AI – MFG Process
MRL By Site
MFG Process Instructions
MFG Process Instructions
MRL Tracked for Each MFG Site Independently for each Part/Assembly
Supplier Factory
AI – MFG Process
MRL By Site
MFG Process Instructions
MFG Process Instructions
MRL Tracked for Each MFG Site Independently for each Part/Assembly


Planning/Scheduling
Requirements (SOW, CQR, Design, etc.)
TDP (all)
MFG Plan (Make, Buy, Where)
Assy & MFG Process Instructions
Build Plans (Qty, Where, When)
Manufacturing Resource Planning (MRP)
Schedule Commitments by Site/Entity
Work Orders (Qty, Where, When)
Purchase Req/Orders (Qty, When)
Manufacturing/Build Process
Lab Description & Resources
MFG Site Resources (MRL Status):
Work Space/Benches, Workforce, Test Equipment, Automation, and Tooling vs. Build Requirements
Parts/Assy's Manufactured

Appendix B: Key Tables in Landscape Layout for Readability

Table 4 - MRL Summaries (MRL Deskbook, 2020)

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

Table 5 - MRL Sub-Thread Objects/Attribute Sample from MBSE Model

Feedback/Input on Artifact Objects Associated with MRL Threads			Instructions - Feedback Requst	Feedback Ratings: 1. Not at all Useful for MRL Rating on this Sub-Thread 2. Not Very Useful for MRL Rating o this Sub-Thread 3. Useful for MRL Rating on this Sub-Thread 4. Very Useful for MRL Rating on this Sub-Thread 5. Absolutely Required for MRL Rating on this Sub-Thread						
MRL Evaluation Threads		Handbook Reference#	MRL Matrix Sub-Thread	Valuable as Artifacts Object or MRL Rating Source?	Feedback Rating (1 to 5)	Measurable Attributes to Track on Objects	Attribute Value Scale	Full Rate Production MRL 10	MRL Level 0 - 4	MRL Level 5
A	Technology & Industrial Base	A.1	Industrial Base	Manufacturer Selection (MFG Plan/Purchasing Orders)		Create/Update MRL Value on Part Number to Manufactuer Location	MRL by Criteria	Deliveries at Full Rate Production	**Target on MFG Plan**	**RFQ or PR Created**
		A.2	Manufacturing Technology Development	Comodity Code (Item Manufactured vs Source Approval)		Commodity Code of Part matches Commodity Code of Manufacture's Rating	No, Proposed, Yes	Yes, Approved	**Proposed**	**Proposed**
B	Design	B.1	Producibility Program	DFMA Score of Design Item (PDM)		Design For Manufacturing Assessments if required by MFG Plan for each PN	N/A, Planned, Done	N/A or Complete	**N/A or Planned**	**N/A or Planned**
		B.2	Design Maturity	Technical Readiness Level (TRL) of Design Item (PDM)		Technical Readiness Level (TRL) assigned on each associated TDP Object	Per TRL Scale	TRL 9	**TRL 4**	**TRL 4**
C	Cost & Funding	C.1	Production Cost Knowledge (Cost modeling)	Target Cost for Item by Marketing or Customer (RFP/RFQ)		Percent of Cost for Lot as compared to Cost Target in MFG Plan for Phase	Cost per Unit Planned	</= Target Cost	**Cost per Plan**	**Cost per Plan**
		C.2	Cost Analysis	Quoted/Actual Cost versus Target (Purchase Contracts)		Percent of Cost for Lot as compared to Cost Target in MFG Plan for Phase	Cost per Unit Planned	</= Target Cost	**Cost per Plan**	**Cost per Plan**
		C.3	Manufacturing Investment Budget	Capital Investments Planned/Committed (Contract/MFG Plan)		Percent of Cost for Lot as compared to Cost Target in MFG Plan for Phase	Cost per Unit Planned	</= Target Cost	**Cost per Plan**	**Cost per Plan**
D	Materials	D.1	Maturity	Technical Readiness Level (TRL) of Design Item (PDM)		Technical Readiness Level (TRL) assigned on each associated TDP Object	Per TRL Scale	TRL 9	**TRL 4**	**TRL 4**
		D.2	Availability	Purchase Request/Orders (Supplier Quotes or commited PO's)		Purchase Order Delievery Date vs Requested Date	PO Finish < Req Date	PO Finish < Req Date	**NA**	**NA**
		D.3	Supply Chain Management	Approved Manufacturer List (Relationship & MRL for each item)		Create/Update MRL Value on Part Number to Manufactuer Location	MRL by Criteria	Deliveries at Full Rate Production	**Target on MFG Plan**	**RFQ or PR Created**
		D.4	Special Handling	EHS Material Handling & Disposal (MFG Plan & Manufacuter Rating)		EHS Requirement on MFG Plan vs EHS Standard of MFG/Lab Site	EHS Rating	Meets MFG Plan Req	**NA**	**Target on MFG Plan**
E	Process Capability & Control	E.1	Modeling & Simulation (Product & Process)	MFG Assembly & Test Flow Documents (HPU, Equipment, CAM Files)		Maturity of MFG Doc with Values vs MFG/Lab Capacity vs MFG Plan Rate	Capacity Capability	Meets Capacity/Rate	**NA**	**Target on MFG Plan**

Table 6 - Mapping of MRL Threads to Information Objects and Key Attributes

MRL Factor	Factor Description	Object with Information	Key Attributes
Technology and Industrial Base:	Capability of suppliers to support production of components/subsystems.	Part/Assy relationship to identified Lab/MFG Site/Supplier	MRL Level of Part/Assy for that Entity based on performance.
Design:	Identification, and control of Key Characteristics.	KPC identified in TDP for all Part/Assy in the design	TRL of TDP
Cost and Funding:	Examines the risks associated with reaching manufacturing cost targets.	Project Budget and Schedule and EVM	CPI/SPI for project
Materials	Risks associated with materials.	Line of Balance	Total Cost of BOM per PO's & Delivery per MRP
Process Capability and Control:	Risks that the manufacturing processes are able to reflect the design intent of key characteristics.	MFG Plan and MFG Process Document indicating MFG Capacity, Cycle Time & Yields	HPU Standard & productivity, Total Cycle Time, First Pass Yields, Scrap/Rework Costs
Quality	Risks and efforts to control quality.	Inspection and ATP plan	Yields, SPC, Cpk per spec's
Manufacturing Workforce (Engineering and Production):	Required skills, availability, and number of personnel to support the manufacturing effort.	MFG Plan and MFG Process Document indicating MFG Capacity, Cycle Time & Yields	HPU Standard & productivity, Total Cycle Time, First Pass Yields, Scrap/Rework Costs, Number of Trained available
Facilities	Capabilities and capacity of MFG facilities	MFG Facility Description Doc	Process Capability/Capacity
Manufacturing Management	MFG Plan to translate the design into an system meeting Program goals	MFG Plan including Ops & Support Staffing Plan	Actual hours of support by each function required

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14. ABSTRACT

The Department of Defense has adopted management tools, such as Manufacturing Readiness Levels (MRLs), which seek to address issues that have delayed the transition to production and delivery of deployment-ready systems. The MRL scale and assessment process institutes periodic reviews of products during the acquisition process. Specifically, MRLs provide a scale to measure, and importantly communicate, progress by evaluating and summarizing multiple aspects of product maturity. Unfortunately, issues are often identified during the periodic assessments which, if addressed earlier, would have further streamlined product delivery. The current research applies Model Based System Engineering tools to analyze and refine organizational structures and the product development process in an attempt to streamline this process. The model includes roles and artifacts involved in transferring requirements and information from design to manufacturing and the process that is applied to convert the Technical Data Package into manufactured components and assemblies. A process for actively tracking information necessary during MRL assessments to provide insight to MRL attainment on a more continuous basis is suggested to improve communication and accelerate the transition to production where appropriate.

15. SUBJECT TERMS

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