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Identification and Management of Key Characteristics in Product Development Using Model Based System Engineering

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ABSTRACT

The International Council on Systems Engineering https://www.incose.org/ is a recognized standards body defining a system engineering knowledge-base, but this knowledge falls short of fully recognizing manufacturing in the Systems Engineering (SE) framework. To be inclusive, Manufacturing needs to join in the initiative of Model Based Systems Engineering to be relevant and succeed in the digital transformation in the field of systems engineering. This paper addresses this need in manufacturing by applying Model Based System Engineering (MBSE) to the identification and management of key characteristics so that a more relevant set of Manufacturing requirements can be introduced into the MBSE construct and help realize manufacturing resilience and become a full SE partner.

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1. INTRODUCTION

Systems Engineering has been defined by various engineering bodies such as the International Council on Systems Engineering, INCOSE. There are departments of Systems Engineering (SE) in many organizations including Defense Acquisition Agencies and COCOMs. The object of a Systems Engineering activity can be observed by the definition given by INCOSE:

"Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods." https://www.incose.org/systems-engineering

One initiative, started in 2007, within INCOSE considers the future of systems engineering that is model based. The new framework, Model Based Systems Engineering (MBSE) would use models and graphical representations replacing document-oriented practices. A definition of MBSE is taken from INCOSE:

"Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation

activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."

The Defense Acquisition University under AT&L Undersecretary of Defense responsibility also closely adheres to the INCOSE Body-of-Knowledge. A review of INCOSE or the DAU body of SE knowledge and most related DOD instructions fail to mention the role of manufacturing as a partner in SE. Manufacturing involvement in the application of MBSE initiatives is essentially non-existent. Refer to the definitions prior where manufacturing development is almost ignored – hiding within the definition as "and later life cycle phases."

Further study into the MBSE space might condense its importance to SE as 1) improved communication; 2) better rendering of complexities and interdependencies and 3) having less risk with changes occur due to the visual representations in architectures and inserting changes into a design component.

Clearly the focus from INCOSE is system behavior and not how the system design must be realized by a manufacturing definition to realize system behavior. There would be no product to function if there was not the necessary structure and behavior of a defined production environment.

Given a personal experience as a subject matter expert in manufacturing (when working for NAVAIR in China Lake and many years in the automotive sector) I had the opportunity to review many manufacturing operations. The effort spanned the largest defense prime contractors and various tier 2 or 3 manufacturing organizations build to print or engineering responsible organizations.

In these reviews it was often through manufacturing risk assessments and product development activities observed. This oversight during product and process development or Engineering and Manufacturing Development (EMD) we would find that the product development stage does not address manufacturing development with the same rigor as product development. In defense acquisition programs it is assumed that if you can fabricate a prototype and qualify the item and its systems, subsystems and components by functional testing the item can be produced effectively – but is that true without a validation of process development?

In summary, the motivation to present this paper the author selects what was observed to be the principal weakness in manufacturing readiness where manufacturing decision processes were not knowledge-based. Oddly, more complex systems did not require what I would call robustness standards such as IATF 16949, AS9145 APQP and PPAP (since 2016) and seldom used AS9103 Control Plan for Key Characteristics. The reliance on product qualification and the First Article Inspection and Test (AS9102) cannot substitute for process validation.

Typically, there were no methods (or standards) to rely upon in the product development cycle that focused on functional or technical performance metrics in the finding of process risk. Process risk assessments that could benefit from Design Failure Modes Analysis activity, if applied, seldom informed process development.

Fewer programs took advantage of any Process Development risk as found in the Process Failure Modes Analysis activity. Even AS9100 or ISO9000 Quality Management System standards fail to address prevention activities in their quality management system definitions, Ireland (2023).

Additional motivation for this paper comes from the finding that 75% of systems fail to meet their reliability requirement and 34% of failures that ground the fleet in NAVAIR are from manufacturing defects. This should be alarming according to Ireland (2017).

Even the NDIA in 2009 recommended that the more disciplined practice that had improved product quality outcomes in the automotive industry be followed that included advanced quality planning and a production part approval process, NDIA (2009).

Couple these alarming statistics of poor production outcomes with those from the GAO that observed weapons programs fail to identify key characteristics and do not know if products can be produced reliably at Milestone C, production start. The GAO for 15 years or more has reported on poor production results related to a lack of manufacturing knowledge such as the finding and management of Key Characteristics for control, Ireland (2017).

The GAO calls the manufacturing maturity needed for program success as Knowledge Point 3 criteria. Programs commonly assess production readiness as a manufacturing maturity through a Manufacturing Readiness Assessment as requiring a Readiness Level of 8. However, the GAO recommends this is insufficient criteria of Manufacturing Readiness and the necessary Level should be Level 9. A manufacturing readiness level (MRL) of 9 would demonstrate programs that have better manufacturing capability. This is equivalent to the application of AS9145 by MS C, production decision. Note: New release of AS9145 will be changed to IA9145 and AS9100 will become IA sanctioned by the International Aerospace Quality Group (IAQG).

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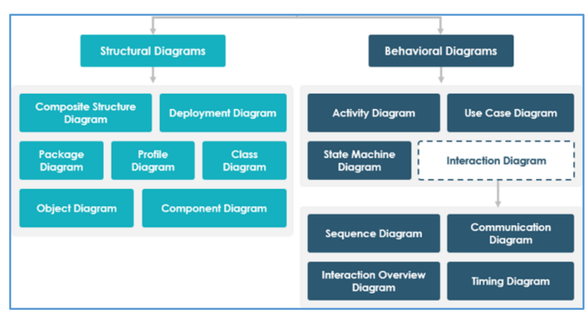
This paper addresses this concern, in part, and will provide an example MBSE process that can be used to help any ground vehicle system development achieve improved quality outcomes at production start. The process, as a best practice, would be superior than without this application assuring homogeneity of process and process control. This KC management approach was used on an actual weapons program that drove a knowledge-based manufacturing capability demonstration for key technologies.

2. MBSE Primer for Manufacturing

MBSE uses a hybrid definition of structural and behavioral diagrams using a language called SysML derived from the software development domain using the Universal Modeling Language or UML.

2.1. MBSE Objective

The objective in an MBSE approach is to create a rendering of a set of requirements that are executable. The modified UML (SysML) language and syntax will be discussed as they occur in later descriptions using the various diagrams that express the application of SysML in MBSE, see Figure 1, **Structural and Behavioral Diagrams**.



From one Behavioral Diagram there is a Use Case Diagram that can define the interaction of a system and the user. There are actors or users and there are activities that can be defined. A use case diagram is a graphic depiction of the interactions among the elements of a system. Use Case development is a methodology in system analysis to identify, clarify, and organize system requirements graphically that describe how user goals may be achieved. The relationships between and among the actors and the Use Case are elegant by their simple rendering visually.

2.2. MBSE - Requirements Definition

There are various types of requirements definition for a system that captures performance objectives and thresholds of a proposed engineered solution. An typical design engineer will capture these requirements at the system level above the detailed specification. There is no similar counterpart in manufacturing to state requirements. In general, creating a representative specification requirement might follow that prescribed by the style described in the guidebook SD15. In one example a requirement expressed in a performance specification for vehicle deceleration might be crafted with the following characteristic expression attributes: (SD 15 is available from American National Standards Institute, ANSI).

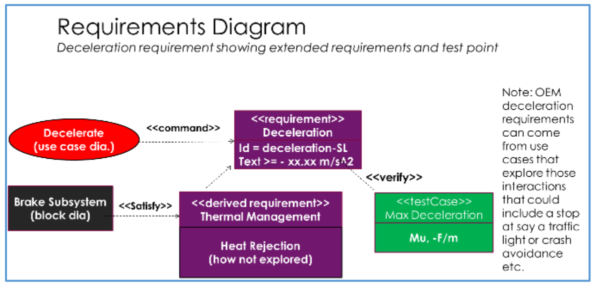
"The performance specification will inform what the item or system shall do in terms of capacity or function of operation. Upper and/or lower performance characteristics are stated as requirements, not as goals or best efforts."

https://webstore.ansi.org/standards/dod/sd15

Example:

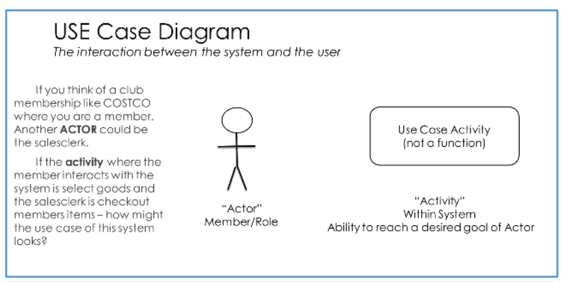
The X9 vehicle system under straight line velocity of 140 kph +/- 5 kph shall demonstrate, at a minimum, a braking (deceleration) that shall satisfy >= -XX.XX m/s^2 continuously until the vehicle shall come to a complete stop given a dry brushed concrete road level to +/-1% grade.

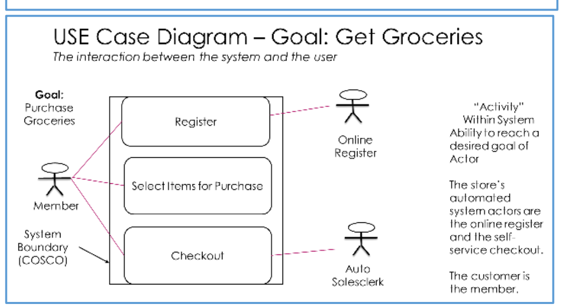
This specification in MBSE framework provides improved communications in specifications as seen in Figure 2, **Requirements Diagram**.



2.3. The Use Case Diagram

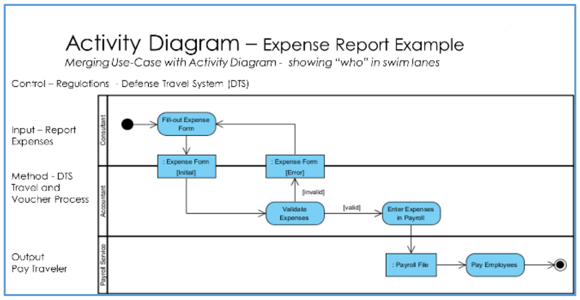
The Use Case Diagram only summarizes some of the relationships between related use cases, actors, and systems. It does not show the order in which steps are performed to achieve the goals of each use case of interest, Figure 3a. **Uses Case Diagram** and Figure 3b. **Use Case Diagram – Goal: Get Groceries**.





2.4. The Activity Diagram

The Activity Diagram is a behavioral diagram that can be applied with swim lanes as shown in the example, see Figure 4, Expense Reporting.



2.5. MBSE and Key Characteristics

Given these simple MBSE tools we can then put it all together and apply it towards a manufacturing development role to realize a key Performance measure or Key Characteristic, KC. The given technologies have associations with parts and mechanisms that result in manufacture of an item that should at some point demonstrate the performance measure or KC. This would be the design intent function that a process is to interact with incoming work products to create the configured item with a key function or key characteristics of design.

The KC identification process relies upon the requirements definition of the system and considers the following typical elements:

<u>Resources to transition to digital (MBSE)</u>

1. Performance Requirements from Higher Order to Lower Order:

Initial Capabilities Documents, Capabilities Development Documents, Key Performance Parameters, Critical Operational Issues, Measures Of Suitability, Measures of Effectiveness, Technical Performance Metrics (TPMs), System Specification, System Engineering Test Plan.

2. Translation into Production Requirements:

QFD Capture / QFD Flow Down
Technical Data Package – Design Analysis, Lists, Drawings; Purchase Orders; Other: Configuration Management Data capture.

3. Organizational Structure: Actors.

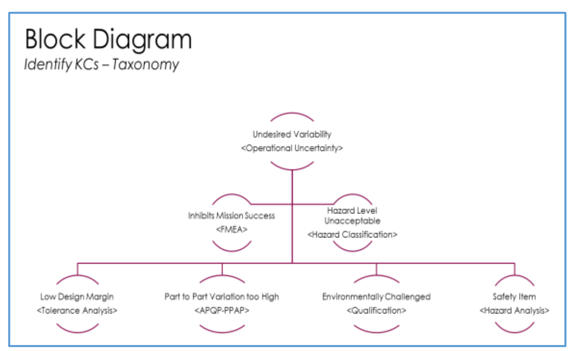
4. Key Activities: Establishing Key Characteristics and Production Control.

5. Identify: Criterion – Cost, Complexity, Performance and Risk – Critical Technology Elements and often related Critical Manufacturing Elements – tools DFMEA/PFMEA.

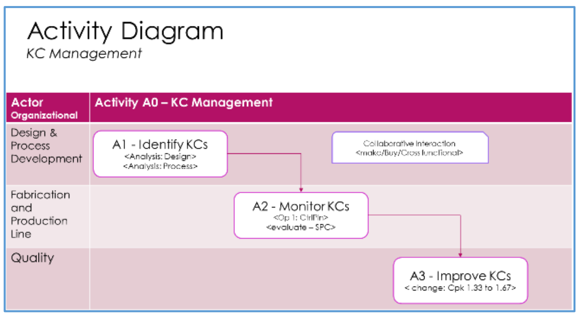
6. Monitor: Data attribute/variable capture and assessment (e.g., Statistical Process Control, SPC) to a configuration and control plan definition.

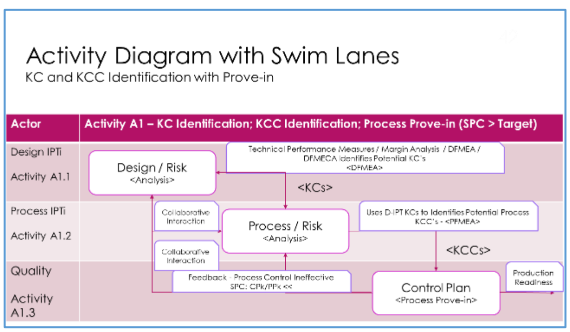
7. Control: Improvement – variability reduction.

Item 5 above can be derived from an interrogation of the design and process risk depicted in MBSE fashion, Figure 5, **Block Diagram**, when selecting a KC for engagement in a control plan. Note: Control Plans can be developed using Aerospace Standard AS9103.



When constructing an activity diagram entitled "A0" with lower activities A1, A2, and A3 it will help define KC management overall with actors from design and process development grouped for activity A1 - Identify KCs. Then fabrication and production line Activity A2 – Monitor KCs. And lastly the Quality actor performing Control Activities A3. Improvement is realized in this phase of product development by variability reduction based on measured sources of variation behavior, Figure 6a, **Activity Diagram** and Figure 6b, **Activity Diagram with Swim Lanes**.





3. Manufacturing MBSE Applied to a Missile System Development

Consider the typical construct of a missile system that highlights technical performance measures or TPMs. The assessment would ask the design what parts or operations in manufacturing will affect the TPM performance. TPM engagement with items of manufacturing are they at risk is some way, see Figure 7 **Block Diagram for KC Taxonomy**. If it does interact with the TPM, say Range is a TPM, then aerodynamics and rocket motor impulse are important.

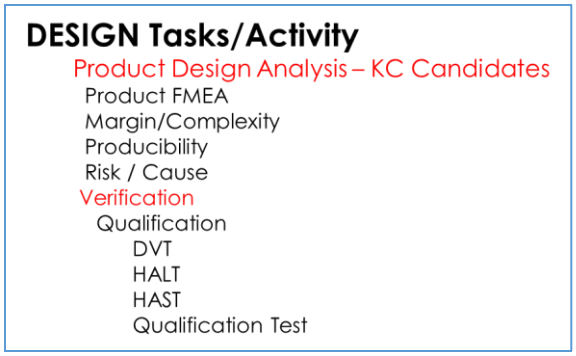
What in manufacturing could adversely affect aerodynamics and hence Range, a TPM. Maybe a screw or rivet on a surface if proud? Can torque alone assure a fastener is flush? If torque and angle controls are applied, then to what tolerances? This leads to a risk that may need a better behavior out of a manufacturing process step.

Also, the cake mix of a rocket motor likewise, what in the mix or assembly environment that could be adverse to the mix creation. Maybe purity of ingredients or humidity if hydrophilic substance if left to ambient too long. One needs to work the items together the activities of product and process design.

There was one engagement where there were 30 design FMEAs that often pointed to manufacturing concerns by design engineering analysis showing some margins of performance were low in early evaluations. It was interesting that none of the DFMEAs were read by the manufacturing team. This violates the SE axiom that it is transdisciplinary and integrated and clearly MBSE depictions would better communicate activities and improved results.

3.1. Product Design Activities

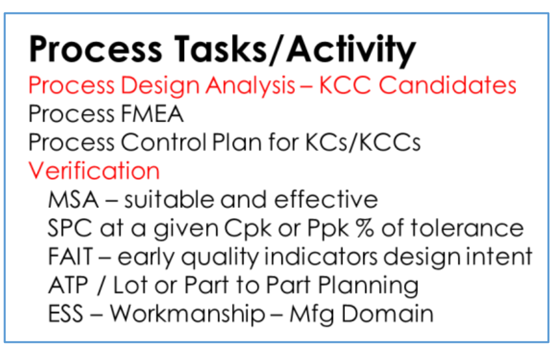
Listed in the figure are typical design tasks or activities to aid in the determination of KCs – TPM care-abouts in program functional requirements and could be communicated in Figure 7, **Design Activity Diagram**.



Product design or Integrated Program Teams responsible as design authorities should be responsible for the KC capture for control engagement in manufacturing analysis and application.

3.2. Process Design Activities

Process Design Activities will showcase a response with the KC identification and develop the monitoring and controls as either preventive or corrective to manage the KCs. In addition, there are the lower-level process Key Characteristics related to the product Key Characteristics. Figure 9. **Process Activity Diagram** with the process operations that influence the Key Characteristic performance are referred to as KCCs with the KCC being the X's that make the Y's.



3.3. MBSE Detailed KC Assessment

From the product and process development one can identify richly the related interactions using Figure 10, **Requirements Flow-down and Feedback** diagram:

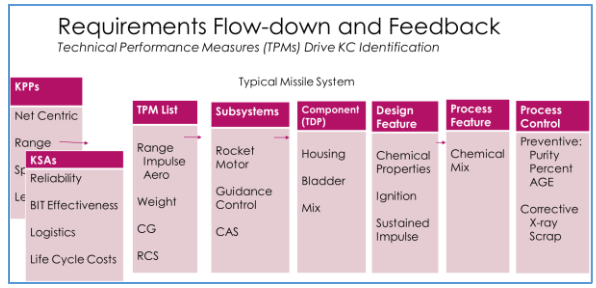
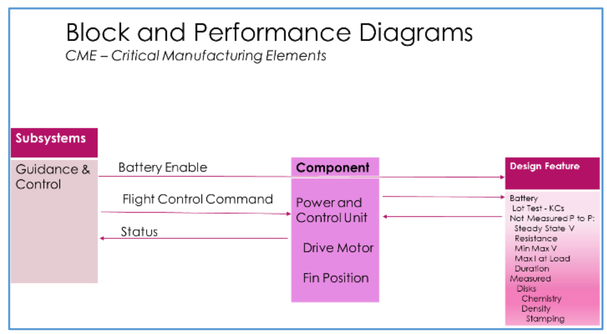
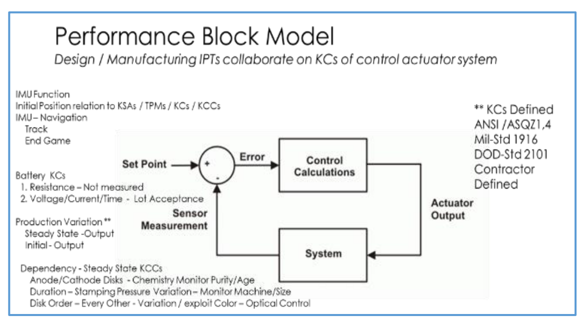


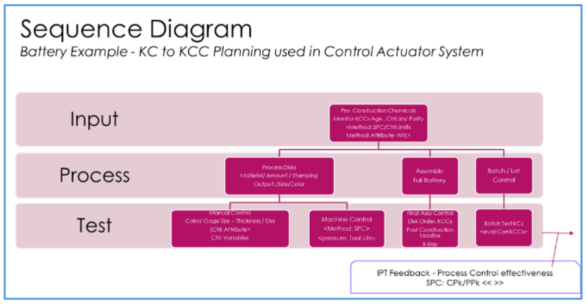
Figure 11, **Block and Performance Diagrams** can help define the relationships between subsystem elements and functional product design characteristics of interest to help interrogate the manufacturing risk and establish relevant control as needed.



This information can be captured directly with performance modeling for a TPM in Figure 12, **Performance Block Model**:



The final MBSE application, Figure 13, **Sequence Diagram,** that fully realizes the manufacturing behavior from use case, design analysis, activity diagram and requirements application that will help advance quality of systems by having manufacturing becoming a full SE partner. I would like to close this discussion by saying that manufacturing only makes designs worse, but the least worse possible.



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