2011 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
SYSTEMS ENGINEERING (SE) MINI-SYMPOSIUM
AUGUST 9-11, 2011 DEARBORN, MICHIGAN

PRODUCIBILITY AND CONFIDENCE INDICES DURING DEFENSE ACQUISITION

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ABSTRACT

Given the complex nature of systems today, systems engineering's primary focus is typically consumed with optimizing function and performance. This condition often causes producibility and cost to become an after-thought, leading to late, over budget production. Therefore an objective and relevant method is required to provide real-time feedback to system engineers relative to producibility and confidence that facilitates better systems design and programmatic decisions.

This paper will discuss the use of producibility model metrics to score several key design elements for the creation of a single standardized producibility index (PI) to encourage engineers to improve their designs for producibility earlier in the development life-cycle. Additionally monitoring certain analysis activities to gauge the level of accuracy in the producibility model will provide metrics to create a single standardized producibility confidence index (PCI) that can be used to mitigate risk in programmatic decision making. Lastly, the On-Board Vehicle Power (OBVP) system will be used to demonstrate the PI and PCI.

INTRODUCTION

Ever evolving needs of the warfighter require defense product development programs to be delivered on time and on budget. GAO studies in 2010 stated that current practices do not adequately identify and objectively quantify producibility and cost issues in the early phases of development (1). These oversights lead to excessive delays, cost overruns, low operational availability and unacceptable sustainment costs. This trend must be reversed in order for the warfighter to benefit from more advanced technology, faster, at lower costs. One way to make this possible is to establish a metric to guide the generation of more elegant and producible defense product designs that will improve soldier effectiveness and reduce logistics lifecycle costs through identification of issues at the early stages. This early identification of issues will reduce the need for block upgrades to provide capabilities and readiness that were initially expected. The NDIA on multiple occasions has referenced this issue of limited focus on producibility in the product development process and the need for a standardized producibility processes and metrics to improve design activities (2; 3).

Over the last few decades corporations have begun establishing product development processes to address producibility concerns. These development processes create design guidelines that provide a standard set of activities to follow in order to optimize producibility. These process definitions delineate what activities should be done, but it is uncommon that there is a standardized metric associated with these activities to qualify how optimized the design has become as result of the activities. A study conducted at the Defense Systems

Management College (DSMC) by Commander David Brown, U.S. Navy, has shown that the use of a producibility index can improve product design (4). This study showed a significant increase in optimization of simple designs due to the use a simple producibility metric. One may extrapolate that a more comprehensive producibility index could be applied to more complex development programs to drive optimization in their designs.

Several different producibility indices have been generated focusing on different key characteristics of the product development process. One of these indices is the Boothroyd and Dewhurst design efficiency index (5). This index uses the Boothroyd Dewhurst Design for Assembly (DFA) scoring system to determine the theoretical current assembly time and optimal assembly time for a design. The ratio of optimal to actual is used as the design efficiency index. The importance of this index is that it serves as a goal for engineers to improve their design to reach the optimal assembly time for their product. The next progression of producibility indices was completed by John Priest and Jose Sanchez in their article *An Empirical Methodology for Measuring Producibility Early in Product Development* (6). Their definition of a producibility index is simply defined as a summation of the key evaluation categories, consisting of each category's difficulty value multiplied by a weighting factor for emphasizing the impact of the category. This method was somewhat limited as it did not directly standardize what design categories should always be evaluated and it only focused on the fabrication of a single part. The method was expanded by a team of system engineers at the Florida International University, redefining the producibility index as a summation of four standard design focus areas (7). These four areas included stock material selection, part size, part weight, and cumulative form feature effects. However, this index still has the limitation of being focused on the fabrication of a single machined part. In contrast another approach to a design evaluation index is the complexity index created by Jones, Hardin, and Irvine in their article, *Simple Parametric Model for Estimating Development (RDT&E) Cost on Large-Scale Systems* (8). This index is an especially important development for design evaluation indices, as it expands the score's focus to the overall system design. The index does this by using communication between components to determine the general complexity of the system. However, the issue with this index is that even though it does look at the overall system design, the score does not focus well on the producibility issues of the design. Recently this concept of a complexity index has been expanded upon by DARPA's Meta Project (9). The expanded complexity index does add terms focusing on part count and part interactions, as a component of the overall complexity of the system. However, in the opinion of our team these terms still provide a rather limited focus of producibility in the design evaluation of this index. Another approach to a design evaluation is the creation of a full producibility model for the product design using commercially available software like Design Profit®. Design Profit® creates a graphical map of the product structure based on the assembly of the product. This model includes assembly time, labor costs, part costs, quality costs, etc. for the creation of a total accounted cost of the product based on the design (10). However, while this model creates several metrics that are indicators of producibility, such as part count, assembly score, quality costs, etc., and it does not provide direct index values to show a definitive increase in the overall producibility of the product's design. For this reason the producibility methodology of Munro & Associates, Inc. is often combined with the producibility model. The producibility model collects the raw producibility metrics of a design, but it is the application of the Munro method that refines these raw metrics into a comprehensive producibility analysis to provide detailed direction to future improvement activities to optimize the product design and manufacturing process. The Munro method does this by first identifying all the inefficiency present in the current design and process. Once this inefficiency is indentified the method generates redesigns that quantify exactly what parts and processes can be eliminated, what will be replacing them, and how much this improves producibility and reduces cost of the overall product (11).

The first goal of this paper is to build upon the aforementioned research to create a new producibility index that provides a comprehensive and standardized producibility score for the overall system design that can be used throughout the product development process. The index's math structure will build off the techniques pioneered in the previous adaptations of producibility indices. The Munro methodology will provide an established producibility perspective and the theory required for this index. Using the Munro method as a basis for the producibility index allows for direct use of the metrics generated in a producibility model of a product. This capability will then allow for automatic calculation of the new producibility index in the model as the analysis of the design is completed.

The second goal of this paper is to build on the 5000.02 and MRL standards to create a producibility confidence index that provides a risk assessment of the knowledge being used to develop the producibility index score. The MRL process has pioneered the establishment of standardized guidance to drive a focus of producibility and manufacturability into the 5000.02 process (12). Specifically the MRL process provides a clear understanding of the exit criteria needed in each phase of the design process, directing engineers to focus on nine key threads to drive producibility. Therefore, since the MRL process has established the importance of the use of this knowledge to create a more producible design, these design threads serve as a foundation for the producibility confidence index developed in this paper.

PRODUCIBILITY INDEX THEORY

The producibility index (PI) provides a single standardized score for the evaluation of the producibility of a design using metrics already developed in a producibility model. The PI can be broken into several sub-scores of key characteristics and tracked through the producibility model in order to better focus engineering effort on critical issues in the product. The DOD MRL process indicates that producibility assessments should begin during the Material Solution Analysis (MSA) phase (13). The PI creates a standardized method for this assessment and provides the capability to initiate assessments earlier during the MSA phase. In order to be comprehensive in the analysis of producibility, but maintain simplicity, four main design focus categories have been determined for the PI.

Main Design Categories

1. Architecture Elegance
2. Value Optimization
3. Assembly Elegance
4. Quality Improvement

Each of the main design categories serves as a tool to focus engineers to key areas of the design known to be leading factors for the development of a producible product. All of the categories further define their focus by the use of two to four sub-categories allowing for the breakdown of a score to facilitate problem resolution in the design. This allows the index to be used as a metric to monitor larger trends of the product design, as well as determining what specific assemblies or components are creating the problems and why. Architecture Elegance scores the interaction of major assemblies in the product design through two sub-categories, subassembly interaction and nesting structure of subassemblies. Value Optimization scores the design of components and their assemblies through two sub-categories, system design and fastener/connector usage. Assembly Elegance scores the assembly of the product through four subcategories, simplicity of the overall assembly process, assembly ease of individual parts and subassemblies, and dwell time. Quality Improvement scores the quality of the assembly process through two sub-categories, cost of quality and variation control.

The score generated for each of the sub-categories is a percentage value indicating the relative optimization of the design in that specific area. To assign a percentage increase in the producibility value for each sub-category a reference is needed for the calculations. For some sub-categories the design goal is to eliminate the value being tracked, and therefore the calculation can be set so the score increases to 100%, as the limit of the tracked value goes to zero. However, for other sub-category scores a standard design goal is required to serve as a numeric reference for the calculation. It is understood that design goals for each sub-category will vary based on product industry and volume levels, but until a full sensitivity analysis can be established to correlate these factors, our team will provide general standard design goals. These standard design goals are taken from best-in-class designs across multiple industries observed during Munro & Associates' 25 year history in product development. This section will discuss the theory for PI scoring, whereas the math structure for the PI equation will be established in a later section.

Architecture Elegance

The first sub-category in Architecture Elegance assigns a design score to underutilization of subassemblies. Subassemblies can be productive assembly design tools, as they allow for independent build-up and testing of several components that can be later installed in the overall product. However, an issue with subassemblies is that they generate waste in the design by requiring additional features, parts, and assembly processes to allow for the interface of the subassembly with the overall product assembly. Therefore in the producibility index a goal will be set for the minimal number of parts required in a subassembly to justify the cost associated with the interface features and components. The use of a minimum of 25 parts per subassembly serves as a good standard goal to guide designs.

The second sub-category in Architecture Elegance assigns a design score to the optimization of the assembly hierarchy structure. As more subassembly levels are added to the product, added delays and handling issues are incurred due to dependency on lower level builds. This typically results in added facility costs as well as requiring expanded supply chain logistics. In order to minimize this added build complexity, a design goal will be set for the optimal number of nested assembly levels. The use of 3 subassembly levels as a maximum serves as a good standard goal for designs.

Value Optimization

The first sub-category in Value Optimization assigns a design score to the optimization of non-fastener and non-connector parts in the product design. Good parts are those parts which are absolutely necessary to deliver the functional requirements of the customer. A part can be considered a good part if it satisfies one of two key characteristics. The first key characteristic is that the part must fundamentally be a different material than the rest of the product in order to achieve the customer requirements for the product's function. The second key characteristic is that the part must move relative to the rest of the product in order to achieve the customer requirements for the product's function. The theory for the creation of these key characteristics is a refinement of the value analysis theory discussed by Miles and Gage (14). Therefore the perfect design would only consist of good parts providing exactly the functionality needed to fulfill the customer's need. However, the realities of a design often cause the generation of additional components to mount or interface good parts. Therefore the use of three non-fastener/connector parts per good part, including the good part, serves as a good standard design goal.

The second sub-category in Value Optimization assigns a design score to the minimization of fasteners and fluid or electrical connectors in the product design. It is important to eliminate fasteners and connectors in a design, as they are a source of inherent waste and poor quality in the product. While fastener piece cost may be relatively low, each fastener added to the design increases assembly complexity variation and fabrication labor costs. Additionally, fastened joints are typically the top driver of mechanical quality issues. Lastly, in order to even use a fastener in a design it will require an engineering analysis of loads on the fastener and the parts to which it interacts. This engineering analysis time could be better used to design features into the interacting parts, allowing for direct mounting of the components without the need of additional fastener parts or ideally combining the fastened parts into a single integrated part. Furthermore, in fluid or electrical systems, interface issues created from connectors for related tubes or cables play a high role in manufacturing and test issues and more importantly, operational availability. Additionally, a significant source of quality issues related to fluid or electrical system design often resides at connection points. Therefore if the system is designed to remove connectors it will increase reliability and producibility of the system.

Assembly Elegance

The first sub-category in Assembly Elegance assigns a design score to the optimization of the overall assembly process in terms of assembly steps. The perfect assembly process would only require the placement of parts to assemble the product. However, the realities of a design often cause additional assembly steps in the process to attach components. To drive optimization the use of nine assembly steps per good part, including addition of parts, serves as a good standard design goal. Specifically nine assembly steps are chosen for the standard design goal because another standard design indicates three parts are allowed per good part, and each part is allowed to have three associated operations.

The second sub-category in Assembly Elegance assigns an ease of handling and placement score based on the assembly scores of each subassembly, part, pre-processed part, and multi-touch. The assembly score is the degree of difficulty assembling parts and subassemblies often referred to as the design for assembly (DFA) or Munro score (10). For the course of this producibility analysis we suggest the use of the Munro method for calculating assembly score. In the Munro method two seconds per part is the absolute optimum design, however, three seconds is a reasonable goal. As the time per part increases it is an indicator of how sub-optimally the part is designed, as it takes longer to collect, orient, and mount the part. Therefore the use of an assembly score of three seconds serves as a good standard design goal for each subassembly, part, pre-processed part, and multi-touch.

The third sub-category in Assembly Elegance assigns a design score to the minimization of manipulations in the assembly process. A multi-touch is when a part or subassembly is handled more than once in the assembly of the product. Once again the perfect assembly process should only include placement of parts to assemble the product. Therefore if a part is required to be touched multiple times, assembly labor time is being wasted. Whenever the operator or the part is required to be manipulated, there is waste in the assembly process. Every change in direction of insertion (CDI) in the assembly process requires labor or machine time to move the tool or part into position. Designs which minimize these reorientations are commonly referred to as “top-down assemblies” where all parts are added strait down from above. Top down assemblies tend to be extremely elegant designs, with minimal waste. Efforts to achieve “top-down assemblies” will have profound impact on the design elegance by leading the team to suggest new ideas to eliminate parts and secondary operations. Additionally if the part requires a manipulation (flip, rotate, etc.) this requires labor or machine time and possible tooling costs. This time and cost could be more effectively used to assemble the subassembly faster and less costly if the subassembly was designed to assembly from the same direction. Therefore if the system is designed to remove manipulations in the process it will increase producibility of the system.

The fourth sub-category in Assembly Elegance assigns a design score to the minimization of dwell time in the assembly process. It is important to eliminate dwell time in an assembly process as it is a source of inherent waste in the product. Operations with dwell time add cost by adding time to the process, and by requiring an inventory of parts in process. Additionally if a quality concern does develop, it can require the scrapping of an entire batch, causing a large cost hit due to the loss of inventory and time.

Quality Improvement

The first sub-category in Quality Improvement assigns a design score to the minimization of Quality Burden (Q-burden). Q-burden is an existing metric based on issue occurrence rate and cost of the occurrence that refers to the cost each completed unit bears to account for scrap, rework, and warrantee. In an ideal product Q-burden should not be a significant contributor to the total cost. Therefore it is important to minimize Q-burden by eliminating quality issues at their source, the design, as much as possible.

The second sub-category in Quality Improvement assigns a design score to the minimization of inspection operations. The perfect design requires no inspections and has no poka yoke issues, since each part has been designed such that it is not possible to assemble the product incorrectly. Excessive inspections indicate uncontrolled processes that require constant checking to ensure the product is properly assembled. Additionally, excessive inspections lead to the generation of wasted cost, as the operation requires a significant amount of time to complete and often requires expensive fixtures and equipment. However, even with the creation of these inspection tools, escaping defects are a well established issue. Often subjective criteria contribute to this phenomenon and drive significant delays to achieve problem resolution consensus. It is important to note that often not all inspection can be removed from an assembly process as some will still be required for validation/functional testing of the final assembly and occasional multi-subassembly modules. Poka yoke issues are included in this term as they are another source of unnecessary inspections in the assembly process due to improper part design for the product assembly. When a poka yoke issue is present in a part it will require the operator to do an informal inspection every time that part is placed resulting in an addition of excessive time to the assembly process. Additionally due to the nature of poka yoke issues they could cause the part to be assembled incorrectly in which case it drives more waste in the assembly process by requiring scrapping or reworking the associated parts. Therefore if the system is designed with zero poka yoke issues and the processes are controlled to eliminate inspection then producibility of the system will increase.

PRODUCIBILITY CONFIDENCE INDEX THEORY

The producibility confidence index (PCI) provides a single standardized score evaluating the amount of production knowledge used in the design and the related confidence in the assessment. This metric acts as a companion evaluation to the PI, as it provides a risk assessment of uncertainty associated with the design producibility stated by the PI. In order to be comprehensive in the tracking of knowledge used in the PI, but maintain simplicity, four main design focus categories have been determined for the PCI.

Main Knowledge Scoring Fields

1. Specification Capture
2. Assembly Knowledge
3. Part Knowledge
4. Infrastructure Knowledge

Each of the main knowledge categories serves as a tool to direct engineers to key analyses that need to be completed in order to have a more accurate producibility index. This allows the index to be used as a quick reference to monitor overall completeness of the producibility analysis, as well as determining what specific assemblies or components still need to be designed and analyzed. This section will discuss the theory for PCI scoring, whereas the math structure for the PCI equation will be established in a later section.

Specification Capture

The Specification Capture category of the PCI assigns a knowledge score associated to specifications captured in the design. This category evaluates the completeness of the overall design structure to ensure the development team has successfully provided for all of the customer specification requirements. If some of the specification requirements have not been captured, then this indicates the design is not complete and will require the addition of subassemblies and components to complete the design.

Assembly Knowledge

The Assembly Knowledge category of the PCI assigns a knowledge score associated to assembly process knowledge captured in the design. This category evaluates the completeness of the assembly, to ensure the development team has successfully analyzed the build process for the assembly of all parts in the final product. If some of the subassemblies have not been analyzed (and are not COTS), then this indicates the design is not complete and will require the addition of assembly steps and components to complete the design.

Part Knowledge

The Part Knowledge category of the PCI assigns a knowledge score associated to subassembly and part knowledge captured in the design. This category evaluates the completeness of the assembly score for each subassembly and part, to ensure the development team has successfully analyzed the handling or re-handling of each subassembly and part in the final product. If some of the subassemblies, pre-processed parts, parts, or multi-touches have not been analyzed, then this indicates the design is not complete and will require the additional analysis of these components to complete the design. Additionally completing this analysis often results in finding added complexity issues that will need to be resolved in the design. This allows time for the generation of several design solutions early in development, as opposed to limited time forcing the generation of only one solution due to late discovery of the problem. Then since these solutions can be implemented early in the product development process the solution is more likely to have a significant positive impact on producibility.

Infrastructure Knowledge

The Infrastructure Knowledge category of the PCI assigns a knowledge score associated to infrastructural knowledge captured in the design through the MRL process. This category evaluates the completeness of the infrastructure analysis, to ensure the development team has successfully analyzed infrastructure required for the assembly of all key critical components in the final product. A low MRL score indicates the infrastructure analysis needed for the design is not complete and will require completion of the MRL process.

PRODUCIBILITY INDEX EQUATION

The equation for the producibility index is the weighted average of the ten sub-category design scores in the format shown below:

$$PI = \frac{1}{\sum_{i=1}^{N} W_i} \sum_{i=1}^{N} (W_i \times P_i)$$

Each sub-category design score (P_i) is calculated using a ratio of the key design factors, that will be explained in the following section. The sub-category scores are based on a 0 to 1 ranking system for easy comparison between sub-categories. To accomplish this 0 to 1 rank, the standard design goal for the sub-category discussed previously is often used. The calculation the producibility score is completed for each of the 10 sub-categories, defining N as equal to 10. Associated with each of the sub-category scores is a coefficient (W_i) that serves as a priority ranking system for each category. These priority ranks are established to direct more development activity in higher value added areas of each design category. For example in the Value Optimization category it is more important to integrate several non-fastener components into one, as opposed to eliminating several fasteners, as there will be higher fabrication issues, engineering development required, and cost associated with non-fastener components. Therefore to provide priority to the term scoring optimization of non-fastener/connector parts, it is considered the primary term for the category and the term scoring minimization of fasteners/connectors is considered the secondary term. The primary term in each category will have its score multiplied by the coefficient W_i equal to one. The secondary term in each category will have its score multiplied by the coefficient W_i equal to one half. The auxiliary term in each category will have its score multiplied by the coefficient W_i equal to one fourth.

Architecture Elegance

The primary sub-category in Architecture Elegance assigns a design score to underutilization of subassemblies. As this is the primary term for this sub-category, the priority coefficient W_1 is equal to one. Utilizing the standard design goal of a minimum of 25 parts per subassembly needed to determine the subassembly as necessary, a ratio of subassemblies above 25 parts relative to the total subassemblies can be used to measure the design in this area. This equation for scoring this subassembly interface cost is shown below:

$$P_1 = \left(\frac{A - B}{A}\right)$$

Where A is defined as total subassemblies in the product, V_A (not shown) is the standard design goal of a minimum of 25 parts in a subassembly, and B is the total subassemblies with less than V_A.

The secondary sub-category in Architecture Elegance assigns a design score to the optimization of the assembly hierarchy structure. As this is the secondary term for this sub-category, the priority coefficient W_2 is equal to one half. If a the standard design goal of a maximum of three subassembly levels is referenced, then a ratio of subassemblies with greater than three assembly levels relative to the total subassemblies can be used to measure the design in this area. This equation for scoring this nested subassembly cost is shown below:

$$P_2 = \left(\frac{A - L}{A}\right)$$

Where A is defined as total subassemblies in the product, V_L (not shown) is the standard design goal of a maximum of three levels of assembly in a subassembly, and L is the total subassemblies with less than V_L.

Value Optimization

The primary sub-category in Value Optimization assigns a design score to the optimization of parts that are not fasteners or connectors in the product design. As this is the primary term for this sub-category, the priority coefficient W_3 is equal to one. Using the standard design goal of three non-fastener/connector parts per good part as a guide, a ratio of the good parts to total non-fastener/connector parts in the product can be used to measure the design in this area. This equation for scoring system design relative to the reduction of secondary parts is shown below:

$$P_3 = \left(\frac{V_G \times G}{P - F}\right)$$

Where V_G is defined as three non-fastener/connector parts per good part, G is the total good parts, P is the total parts in the product, and F is the total fasteners in the product.

The secondary sub-category in Value Optimization assigns a design score to the minimization of fasteners and connectors in the product design. As this is the secondary term for this sub-category, the priority coefficient W_4 is equal to one half. As discussed previously it is important to eliminate fasteners and connectors in a design, therefore a ratio of non-fastener/connector parts to total parts is established such that as the number of fasteners and connectors drives to zero, the scoring ratio drives to one. This equation for scoring minimization of fastener and connector usage is shown below:

$$P_4 = \left(\frac{P - F}{P}\right)$$

Where P is defined as the total parts in the product, and F is the total fasteners and connectors in the product.

Assembly Elegance

The primary sub-category in Assembly Elegance assigns a design score to the optimization of the overall assembly process. As this is the primary term for this sub-category, the priority coefficient W_5 is equal to one. Utilizing the standard design goal of nine assembly steps per good part, the ratio of good parts relative to assembly steps can be used to measure the design in this area. This equation for scoring the manufacturing process is shown below:

$$P_5 = \left(\frac{V_S \times G}{S}\right)$$

Where V_S is defined as the standard design goal of nine assembly steps per good part, G is the total good parts in the product, and S is the total assembly steps.

The secondary sub-category in Assembly Elegance assigns a design score to the optimization of the assembly score in the design for ease of handling and placement. As this is the secondary term for this sub-category, the priority coefficient W_6 is equal to one half. This term is the average of the ratio between the standard Munro assembly score design goal relative to actual Munro assembly score for each subassembly, pre-processed part, part, and multi-touch in the product design. This equation for scoring part design for assembly is shown below:

$$P_6 = \frac{1}{Z}\sum_{i=1}^{Z}\left(\frac{V_R}{R}\right)$$

Where Z is defined as the total of all the subassemblies, pre-processed parts, parts, and multi-touches in the design, V_R is the standard design goal of a Munro assembly score of three seconds, and R is the Munro assembly score for each subassembly, pre-processed part, part, or multi-touch.

The first auxiliary sub-category in Assembly Elegance assigns a design score to the minimization of manipulations in the assembly process. As this is an auxiliary term for this sub-category, the priority coefficient W_7 is equal to one fourth. As discussed previously it is important to eliminate manipulations in the assembly process, therefore a ratio of manipulations to total assembly steps is established such that as the number of manipulations drives to zero, the scoring ratio drives to one. This equation for manipulation efficiency is shown below:

$$P_7 = \left(\frac{S - M}{S}\right)$$

Where S is defined as the total assembly steps in the process and M is the total manipulation used in assembly.

The second auxiliary sub-category in Assembly Elegance assigns a design score to the minimization of dwell time in the assembly process. As this is an auxiliary term for this sub-category, the priority coefficient W_8 is equal to one fourth. As discussed previously it is important to eliminate dwell time in a design, therefore a ratio of non-dwell throughput assembly relative to total throughput assembly time is established such that as the amount of dwell time drives to zero, the scoring ratio drives to one. This equation for scoring dwell time usage is shown below:

$$P_8 = \left(\frac{T - D}{T}\right)$$

Where T is defined as the total throughput assembly time and D is the total throughput dwell time.

Quality Improvement

The primary sub-category in Quality Improvement assigns a design score to the minimization of Q-burden. As this is the primary term for this sub-category, the priority coefficient W_9 is equal to one. As discussed previously it is important to eliminate Q-Burden in a design, therefore a ratio of non-Q-burden cost relative to the total accounted cost of the product is established such that as the amount of Q-burden drives to zero, the scoring ratio drives to one. This equation for scoring the reduction of Q-burden is shown below:

$$P_9 = \left(\frac{C - Q}{C}\right)$$

Where C is the total accounted cost of the product and Q is the total Q-burden.

The secondary sub-category in Quality Improvement assigns a design score to the minimization of inspection operations and poka yoke issues. As this is the secondary term for this sub-category, the priority coefficient W_{10} is equal to one half. As discussed previously it is important to eliminate inspections and poka yoke issues in the design, therefore a ratio of inspections and poka yoke issues to total assembly steps is established such that as the number of inspections and poka yoke issues drives to zero, the scoring ratio drives to one. This equation for scoring inspection usage and poka yoke issues is shown below:

$$P_{10} = \left(\frac{S - Y}{S}\right)$$

Where S is defined as the total assembly steps in the process and Y is the total number of inspections and poka yoke issues.

PRODUCIBILLITY CONFIDENCE INDEX EQUATION

The equation for the producibility confidence index is the average of the four category knowledge scores in the format shown below:

$$PCI = \frac{1}{N}\sum_{i=1}^{N} PC_i$$

Each of the category knowledge scores are calculated using a ratio of the key design knowledge factors controlling each specific focus area. The category knowledge are created such that each of the scores will fall on a 0 to 1 scale allowing for easy comparison between categories and the proper calculation of the overall PCI using comparable indexed scores. In this calculation the knowledge score is completed for each of the 4 sub-categories, defining N as equal to 4. Additionally as the score increases toward a value of 1 it shows the increase of knowledge about the design and can provide a rough percentage score as to relative progress toward the completion of the design.

Specification Capture

The Specification Capture category of the PCI assigns a knowledge score associated to specifications captured in the design. Therefore the ratio of design specification captured in the design is set relative to the total design specifications needing to be addressed in the product such that as the amount of specifications captured in the design increase, the scoring ratio drives to one. This equation for scoring specification capture is shown below:

$$PC_1 = \left(\frac{R_C}{\mathrm{R_T}}\right)$$

Where R_C is defined as the design specification captured and $\mathrm{R_T}$ is the total number of design specifications.

Assembly Knowledge

The Assembly Knowledge category of the PCI assigns a knowledge score associated to assembly process knowledge captured in the design. Therefore the ratio of subassemblies with completed analyzed manufacturing process is set relative to the total subassemblies in the product such that as the amount of subassemblies analyzed in the design increase, the scoring ratio drives to one. This equation for scoring assembly knowledge is shown below:

$$PC_2 = \left(\frac{S_A}{A}\right)$$

Where S_A is defined as the total analyzed subassemblies and A is the total subassemblies in the product.

Part Knowledge

The Part Knowledge category of the PCI assigns a knowledge score associated to subassembly and part knowledge captured in the design. Therefore the ratio of subassemblies, pre-processed parts, parts, and multi-touches with Munro assembly scores is set relative to the total subassemblies, pre-processed parts, parts, and multi-touches in the product such that as the amount of subassemblies, pre-processed parts, parts, and multi-touches analyzed in the design increase, the scoring ratio drives to one. This equation for scoring part knowledge is shown below:

$$PC_3 = \left(\frac{P_Z}{Z}\right)$$

Where P_Z is defined as the total analyzed subassemblies, pre-processed parts, parts, and multi-touches and Z is the total number of subassemblies, pre-processed parts, parts, and multi-touches in the product.

Infrastructure Knowledge

The Infrastructure Knowledge category of the PCI assigns a knowledge score associated to infrastructural knowledge captured in the design through the MRL process. Therefore the average of the ratios between the MRL ranks for each key critical component set relative to the MRL rank of 9, established at full rate production, is used as a measurement for this knowledge area of the design. This equation for scoring infrastructure knowledge is shown below:

$$PC_4 = \frac{1}{C}\left(\sum_{i=1}^{C}\left(\frac{MRL}{9}\right)\right)$$

Where C is defined as the total number of key critical components in the product and MRL is the Manufacturing Readiness Level of each key critical component. Note that if there is no component or process deemed to be key critical requiring a MRL assessment, then this term should be set to a value of one.

APPLICATION OF PRODUCIBILITY INDICES

In the past the On-Board Vehicle Power (OBVP) system and specifically the Generator System Controller (GSC) was used to demonstrate how producibility modeling can improve a system's design (15). This study will build on that process by using metrics from the original producibility model of the GSC Phase I design, and compare them with metrics from a new producibility model of the current GSC Phase II design. These metrics from the Design Profit® producibility models will provide all the required inputs into the PI and PCI equations. Table 1 shows these metrics set as percentages relative to the values in the original GSC Phase I design baseline.

	GSC Phase I	GSC Phase II
Total Subassemblies	100%	89.8%
Subassemblies < 25 Parts	100%	108.8%
Subassemblies > 3 Levels	100%	100.0%
Good Parts	100%	100.0%
Parts	100%	69.6%
Fasteners and Connectors	100%	73.0%
Assembly Steps	100%	68.5%
Total Assembly Score	100%	62.4%
Subassemblies, Parts, & Multi-Touches	100%	67.2%
Multi-Touches, CDIs, & Manipulations	100%	55.2%
Throughput Assembly Time	100%	72.0%
Assembly Dwell Time	100%	100.0%
Total Cost	100%	112.1%
Q-Burden	100%	67.0%
Inspections and Poka Yoke Issues	100%	68.7%

Table 1: Producibility modeling metrics used in PI equation

The metrics shown in Table 1 indicate that the GSC Phase II design is a significant improvement over the GSC Phase I design. This is thanks to the integration of producibility modeling into the system engineering process when they were creating the GSC Phase II design. However, these metrics by themselves to not directly state what area of producibility the design has truly improved and where is there the possibility for further improvement. Therefore to clarify what makes the GSC Phase II more producible than the GSC Phase I, these metrics were input into the PI. The producibility sub-category scores and overall PI score are shown in Table 2.

PI Term	GSC Phase I	GSC Phase II	% Change
P_1	42.37%	30.19%	-28.75%
P_2	94.92%	94.34%	-0.61%
P_3	5.08%	7.53%	48.07%
P_4	62.21%	60.37%	-2.95%
P_5	2.23%	3.25%	46.02%
P_6	26.86%	29.43%	9.59%
P_7	70.96%	76.59%	7.93%
P_8	100.00%	100.00%	0.00%
P_9	63.41%	78.13%	23.22%
P_{10}	94.40%	94.38%	-0.02%
PI	45.39%	46.54%	2.54%

Table 2: PI sub-category and overall scores

There are two ways to view the results of a PI calculation. The first is to review the overall PI score to see if it is trending in the positive direction, which is the case for the GSC Phase II. This confirms that the overall producibility of the product has increased and the new design is better than the previous design. The second view, and possibly the more important usage of the PI, is to review each of the PI sub-category scores to see why PI has changed as much as it did. This review can then be used a tool to direct future development work on the design to specific areas with the most opportunity to improve producibility. For example the GSC Phase II has positive increases in most of the sub-category scores, however, the scores for P_1 and P_4 are showing decreases. P_1 is the term referring to the underutilization of subassemblies, and a decrease in this score would indicate that several smaller subassemblies have been generated in the new design relative to previous design. Therefore future design work would include added effort to integrate subassemblies to better utilize fewer subassemblies and reduce costs. P_4 is the term referring to fastener/connector usage, and a decrease in this score would indicate that when several non-fastener parts were integrated in the design, the associated fasteners were not reduced as well. This could be the result of several possibilities. One possibility is that the increase in subassemblies has led to the use of more fasteners and connectors for attachment and subassembly interfaces. Another possibility is that the new integrated parts may be using more fasteners than required. Therefore the future design work would be to review the design for opportunities to reduce the number of fasteners and connectors. However, while showing positive increases does indicate improvement in a sub-category score, it does not necessarily mean that additional engineering support is not required in a specific area. For example the GSC Phase II shows significant increases in P_3 and P_5 scores, but when the main score is reviewed it shows the design is rather low in those select areas. What this means is that the design team did an excellent job to improve these areas over the previous design, however, focus needs to be continually directed to these areas as there is still a great opportunity to improve producibility in that area. Specifically P_3 and P_5 refer respectively to the overall optimization of parts and overall optimization of the assembly process relative to the theoretical good parts of the design. For most industries the score for these terms will often indicate opportunity for improvement. This is because the best way to drive producibility into a design is to try and design a product with the least number of parts and least number of assembly process steps. The product with fewer parts requires less part design and fabrication, and the assembly process with fewer steps is easier to control and takes less time to complete.

However, if the PI scores of the two designs are coming from different producibility models with different levels of detail, then the trends being reviewed in the analysis of the PI could be misleading. Therefore in order to confirm that PI scores are comparable with similar levels of detail being analyzed, the PCI should always be stated alongside the PI score. The category scores and overall score for the PCI of the GSC Phase I and Phase II designs can be seen in Table 3.

PCI Term	**GSC Phase I**	**GSC Phase II**
PC_1	100.00%	100.00%
PC_2	77.97%	81.13%
PC_3	100.00%	100.00%
PC_4	100.00%	100.00%
PCI	94.49%	95.28%

Table 3: PCI category and overall scores

First, it is important to note that this example compares the GSC phase I and II, which are completed designs. Therefore the PC_1, which refers to specification capture, is at 100% as the completed designs captured all customer requirements. PC_2 which refers to analyzed subassemblies is not at 100% as a few of the subassemblies within the model were not considered in scope at the time of the analysis, and so were not analyzed. Additionally due to the fact that the designs were completed, PC_3 which refers to subassembly, part, and multi-touch scoring, was at 100% as all parts had been analyzed for the design. Lastly, PC_4 which refers to MRL is at 100% as the GSC is considered to use common components and manufacturing process, therefore nothing is indentified as key critical so the term is set to 100%. If this index is used earlier in the development process it would show lower category scores from a reduced amount of detail in the producibility model. What these scores indicate is that both of the GSC Phase I and Phase II producibility models have comparable levels of detail. This means that PI scores of both designs can be compared without concern.

It is important to note that even if two designs do have similar PCI scores it does not necessarily mean their PI scores can be compared. We expect that individual standard design goals within the sub-category scores of the PI will differ across industries, product classes, sizes, and volumes. Also different designs will have different levels of requirement for design performance that might inherently reduce producibility. Therefore at this point in our development of the PI and PCI, only designs for the same application with similar PCI scores can have their PI scores compared for analysis.

FUTURE WORK

It is the hope of our team to continue to expand upon the producibility indices with a full sensitivity analysis that will better refine the values used for the design goals of each sub-category. This sensitivity analysis would investigate product industries, classes, volume levels, and size to determine how these affect the expected design goals. At the completion of this future study we would integrate weighting factors to these established design goals in order to provide improved PI and PCI scales that can provide a metric across defense programs. The weighting of these factors should provide universal PI and PCI scales regardless of product industries, classes, volume levels, and size. This would expand the benefit of these indices to provide standard global grading for any defense program and allow these indices to be applied to the 5000.02 and MRL timeline and grading scales.

CONCLUSION

It is the goal of all engineers to find the optimal solution to a problem. The hope of our team is that the producibility index (PI) and the producibility confidence index (PCI) detailed in this paper will serve as a powerful tool to help engineers to optimize their designs. Specifically the 10 sub-categories of the PI should provide indications to engineers where opportunities exist in their design to improve producibility. This analysis of opportunities will also reduce risk thanks to the PCI providing an indication as to the level of detail being used in the analysis. This theory has been demonstrated effectively with the On-Board Vehicle Power (OBVP) design team for the Generator System Controller (GSC). However, there is significant room for improvement in the producibility indices. Specifically the continuation of refinement in the standard design goals and priority coefficients will allow the scores in the PI and PCI to better indicate when changes in producibility have occurred and properly weight the importance of that change to show the impact on the overall product design. Additionally the PI and PCI have been applied to the completed design analyses of the GSC Phase I and II to show common trends in a product that has been redesigned to become more producible. However, the real strength of the theory behind the PI and PCI is that it can be applied early in product development and continue to be used throughout the process to guide design decisions. Therefore the best way to demonstrate the true value and effectiveness of the PI and PCI would be to apply the indices at the beginning of development and show the use throughout the development process.

Hopefully the producibility indices theory discussed in this paper will be able to expand to provide the foundation for the establishment of the PI and PCI as a standard design evaluation allowing for a common technique to be applied across the system engineering community. This will then enable system engineering to use a common language across industries to discuss the improvement of producibility in their products, thereby providing the DOD a way to achieve their goals to improve asset uptime while reducing the initial costs and eliminating the possibility of cost overruns. The PI and PCI will enable the systems engineering community to establish a new trend that allows the warfighter to benefit from more advanced technology, faster, at lower costs.

ACKNOWLEDGEMENTS

This work was funded in part by the Defense-wide Manufacturing Science and Technology Program (FA-8650-10-C-5702), led through the Office of the Secretary of Defense, Manufacturing Technology. The authors would like to thank Jennifer Fielding and Brench Boden of the Air Force Research Laboratory, Manufacturing Technology Division, for their technical assistance and guidance on this program.

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APPENDIX

Expanded Producibility Index Equation:

$$PI = \frac{2}{13}\left(\left(\frac{A-B}{A}\right) + \frac{1}{2}\left(\frac{A-L}{A}\right) + \left(\frac{V_G \times G}{P-F}\right) + \frac{1}{2}\left(\frac{P-F}{P}\right) + \left(\frac{V_S \times G}{S}\right) + \frac{1}{2}\left[\frac{1}{Z}\sum_{i=1}^{Z}\left(\frac{V_R}{R}\right)\right] + \frac{1}{4}\left(\frac{S-M}{S}\right) + \frac{1}{4}\left(\frac{T-D}{T}\right) + \left(\frac{C-Q}{C}\right) + \frac{1}{2}\left(\frac{S-Y}{S}\right)\right)$$

Standard Design Goal Parameters:

1. V_A = Standard Minimum Parts per Subassembly = 25
2. V_L = Standard Assembly Levels = 3
3. V_G = Standard Non-Fastener/Connector Parts per Good Part = 3
4. V_S = Standard Assembly Steps per Good Part = 9
5. V_R = Standard Munro Assembly Score = 3
6. N = Number of Scoring Terms = 10

Variables:

1. A = Total Subassemblies
2. B = Number of Subassemblies with Less than V_A Parts
3. L = Number of Subassemblies with Less than V_L Assembly Levels
4. G = Total Good Parts
5. P = Total Parts
6. F = Total Fasteners and Connectors
7. S = Total Assembly Step Count
8. R = Assembly Score Subassemblies, Pre-Processed Parts, Parts, or Multi-Touches
9. Z = Total Subassemblies, Pre-Processed Parts, Parts, and Multi-Touches
10. M = Total Multi-Touches, Changes in Direction (CDI), and Part Manipulations
11. T = Total Throughput Assembly Time
12. D = Total Assembly Dwell Time
13. C = Total Cost
14. Q = Total Q-Burden
15. Y = Total Inspections and Poka Yoke Issues

Expanded Producibility Confidence Index Equation:

$$PCI = \frac{1}{4}\left(\left(\frac{R_C}{\mathrm{R_T}}\right) + \left(\frac{S_A}{A}\right) + \left(\frac{P_Z}{Z}\right) + \frac{1}{C}\left[\sum_{i=1}^{C}\left(\frac{MRL}{9}\right)\right]\right)$$

Standard Knowledge Parameters:

1. N = Number of Scoring Terms = 4

Variables:

2. R_T = Total Specification Requirements
3. R_C = Spec. Requirements Captured with Analyzed Parts
4. A = Total Subassemblies
5. S_A = Total Analyzed Subassemblies
6. Z = Total Subassemblies, Pre-Processed Parts, Parts, and Multi-Touches
7. P_Z = Total Analyzed Subassemblies, Pre-Processed Parts, Parts, and Multi-Touches
8. C = Total Critical Parts Requiring MRL Scoring
9. MRL = Manufacturing Readiness Level