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MANUFACTURABILITY ASSESSMENT KNOWLEDGE-BASED EVALUATION (MAKE) AND A PILOT CASE STUDY

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Abstract

Understanding the manufacturability concerns of a product design is a crucial part of a successful product introduction. The literature suggests that a significant portion of a products life cycle costs is committed in the early design phase and that manufacturability concerns are one of the major drivers of these costs. The lack of insight into the manufacturability of a design can potentially lead to expensive design iterations, tooling modifications, the potential for rework and other factors all resulting in costly delays and other potential risks to product introductions. As a result, there is a benefit in the development of a practical way to assess the manufacturability of a design.

This paper focuses on the enhancements of a methodology for performing manufacturability assessments of product designs. This new approach, referred to as Manufacturability Assessment Knowledge-based Evaluation (MAKE), utilizes a taxonomy of key aspects of manufacturability combined with subject matter experts (SMEs) to assess a product design. The results from MAKE include detailed manufacturability concerns along with recommendations for improvement. A pilot software tool was developed to guide the assessor through the process. A discussion of this methodology within the context of a defense industry case study is presented, along with lessons learned and recommendations.

Keywords

Manufacturability, Assessment, Metric, Life Cycle, Taxonomy

Introduction

The impact of design activity on life cycle cost is significant and well known among researchers and practitioners. The literature indicates that approximately 80% of the life cycle costs are committed during the product design phase (Anderson (2014), Dunk (2004), Rush & Roy (2000)) with manufacturing costs being a significant portion of those costs. Therefore, addressing potential concerns that may affect manufacturing costs should be considered during the early phase of the product development. It is at this stage where the practice of design for manufacturability (DFM) is most critical. While DFM is well documented, review of the literature yielded minimal information pertaining to the manufacturability assessment of a total system (i.e. total product) design nor development of a metric to represent the manufacturability of a total product. This research continues to support the development of such a methodology that will assess the manufacturability of a product in a system design cycle. For the purpose of this research, manufacturability is defined as '*the ease with which a product or component can be produced…and the freedom that its design has from inherent quality and processing problems*' (Bralla, 1996). Included in this simple definition are many factors that must be considered in order to ascertain a fundamental understanding of the manufacturing challenges associated with a product's design.

The basis of the Manufacturability Assessment Knowledge-based Evaluation (MAKE) taxonomy involves the assessment of a product design to identify manufacturability concerns. This judgment based assessment, involving the use of a cross-functional team of subject matter experts (SMEs), is intended to provide a relevant and thorough assessment of a product design. The resulting assessment includes a metric representative of manufacturability of the system, identification of key aspects of the design that adversely affect the product's manufacturability, and a list of design recommendations aimed at mitigation of the impact of the identified concerns. This provides a basis for improving the manufacturability of the design (McCall, Walden, Gedik, et al., 2016).

The details within this paper reflect on the prior research in manufacturability, present the advancements in the development of the manufacturability assessment methodology, and provide insights gained from the application of the methodology to a pilot case study. In addition, this paper introduces a new software tool developed for use in conducting manufacturability assessments.

Background

The overall assessment of a conceptual design involves attributes, which are highly judgmental. These types of judgments can be informed via operational and physics based models and simulations that often require high-speed computing capabilities. However, prior to that stage, the foundation of how to assess manufacturability of an entire system must be established. The initial stage of this research was focused on the development of the methodology and application of the methodology to a pilot case study. This is detailed in a prior technical report authored by the research team (McCall, Walden, Dalton, et al., 2016).

The overarching intent of the research involves the development of a manufacturability assessment that utilizes a manufacturability metric to perform tradeoff analyses between different variations of a design in support of the Department of Defense (DoD) ERS Tradespace efforts.

Engineered Resilient Systems (ERS)

While it is generally acknowledged that product design decisions made early in the initial phases drive costs throughout the product life cycle, it is also true that virtual or low fidelity designs are very difficult to assess for manufacturability with a high degree of technical acuity. Development of a tradespace tool capable of evaluating product designs and providing a manufacturability metric is one of the strategic objectives of the ERS program, which is one of the seven stated priority science and technology investment areas for the DoD. "*For systems to be included in the force structure, they need to be manufacturable, sustainable, easily modifiable, and cost effective*" (Goerger, Madi, Eslinger, 2014). Accordingly, this research concentrates on the development of the manufacturability assessment methodology intended to provide input to the ERS tradespace development effort.

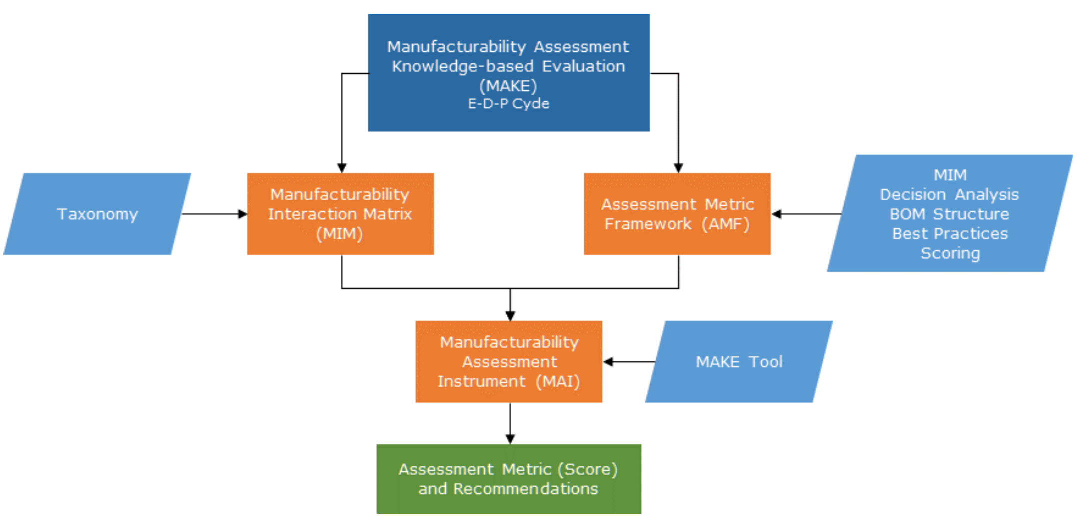
A significant area of ERS tradespace development involves life cycle costs, which include manufacturing costs. Some of the factors that drive manufacturing costs are identifiable, practical aspects of manufacturability (e.g. material properties, tooling, material handling, etc.) but some resultant costs (scrap, inefficiencies, other waste) are not as predictable. In order to effectively gauge the manufacturability of a design, all of these manufacturing cost drivers must be considered to the extent for which the available design information provides.

MAKE Development

The Research Approach

The general structure of the approach to the manufacturability research consists of three areas, illustrated in Exhibit 1 (McCall, Walden, Dalton, et al., 2016).

Exhibit 1. Diagram of the Approach to the MAKE Research.



The Manufacturability Interaction Matrix (MIM). The MIM is a taxonomy-based system used to classify the key criteria of manufacturability. The matrix serves as the basis for the assessment and is used to provide a structured process for evaluating parts and assemblies within a given design.

Assessment Metric Framework (AMF). The framework utilizes the application of the interaction matrix to a judgment based evaluation system. The assessment occurs based on a Bill of Material (BOM) structure, review of physical components, or renderings of the design. The intent of the assessment would include scores of the parts and assemblies to be rolled up to an aggregated metric score. This assessment of the parts and assemblies occurs within the context of the Evaluation-Diagnosis-Prescription (E-D-P) cycle (Walden & Greenwood, 2009). The evaluation phase includes a detailed review of the parts/assemblies by the assessment team. It is in this phase of the process that the MIM is utilized to provide individuals scores for the parts/assemblies. The next step in the process includes the diagnosis phase where the scores and the detailed information gathered in the evaluation phase are utilized to identify the manufacturability concerns associated with the design. Once those concerns are identified, the assessment enters the prescriptive phase. This includes development of an inclusive list of recommendations aimed at mitigation of the concerns identified in the diagnosis phase. As action is taken on these recommendations to improve the design's manufacturability, the cycle continues with evaluation of the next iteration of the design.

The Manufacturability Assessment Instrument (MAI). This is envisioned as a software tool (later referred to as the MAKE tool) used by the assessor to input judgments, calculate the manufacturability scores and compile recommendations about the product design to the manufacturer. The tool serves as mechanism to work through the process of the manufacturability assessment of the product. Ultimately, the results of the entire assessment will be communicated to the end customer, providing them with a clear understanding of the manufacturability concerns and the actions necessary to improve the manufacturability of the design.

Improvements to the Research

Matrix/Taxonomy. The MIM identifies the interaction of key aspects of design and manufacturing. The taxonomy was first formulated to answer the question, '*what is the impact of a particular aspect of design on a particular aspect of manufacturing?'* with each X in the matrix representing those interactions (Note: some interactions have no impact as indicated by blank cells in the matrix). The initial V1.0 of the taxonomy for MAKE was developed based on 15x9 matrix as shown on the left of Exhibit 2 (McCall, Walden, Dalton, et al., 2016). The application of this matrix in the assessment of a pilot case study from prior year's work yielded some insight into several key areas of improvement needed in the MAKE taxonomy. These lessons learned were used to develop V2.0 of the MIM shown on the right side of Exhibit 2 (McCall, Walden, Dalton, et al., 2017).

Exhibit 2. Manufacturability Interaction Matrix (MIM), V1.0 and V2.0.

Aspects of Design / Aspects of Mfg	Design	Material	Product Dimensioning	Special Tools	Part Geometry	Special Skills	Ease of Assembly	Reliability	Process Capability	Capacity and Scalability	Ergonomics	Material Handling, Transporting, and Packaging	Strategic Sourcing	Quality Testing and Equipment	Maintainability
Process	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Supply Chain	X	X			X	X				X	X	X		X	X
Equipment/Tools	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Facility	X			X	X					X	X	X	X	X	X
Labor	X						X		X	X	X	X	X		
Quality	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Cost	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
EHS	X	X		X	X	X	X			X		X	X	X	
Sustainability	X	X		X	X		X				X			X	

Aspects of Design / Aspects of Mfg	Material	Product and Manufacturing Information (PMI)	Design Geometry
Process	X	X	X
Process Capability	X	X	X
Supply Chain	X	X	X
Equipment/Tools	X	X	X
Facility	X	X	X
Labor	X	X	X
Quality	X	X	X
EHS	X	X	X
Ergonomics	X	X	X
Capacity and Scalability	X	X	X
Maintainability	X	X	X

MAKE Framework. The topic of assessments involves the challenge of developing a methodology that is used to evaluate a system of interest (e.g., manufacturing enterprises, product design). Examples of this type of assessment found in the literature include the Malcolm Baldrige National Quality Award (MBNQA), the Shingo Prize, Lean

Enterprise Self-Assessment, and ISO 9000. The development of these methodologies often involves the use of judgmental ratings where issues of reliability and validity are of concern (Coleman, Van Aken, & Shen, 2002), (Lee. S.M., Rho, & Lee, S.G. 2003).

The ratings from the assessment domain generally reflect the conformance of the appraised item to a scaled reference model derived from a taxonomy (e.g., MBNQA criteria, the Shingo Model, Lean Enterprise Self-Assessment, Manufacturing Enterprise Taxonomy, and Manufacturability Taxonomy). This class of assessments is referred to as taxonomy based assessment methodologies.

MAKE has some similarity to these types of assessments. However, instead of comparisons made to a standard or reference model, comparisons are made among alternative designs. The metric scores between multiple alternatives provide the customer with insight into the risk level and cost drivers between design alternatives. The detailed information that is part of the assessment becomes the basis to diagnose these cost drivers and provide recommendations for improvement. Thus, allowing the customer to make tradeoffs in order to improve the metric scores.

Woven throughout the framework of MAKE is the use of subject matter experts to assess the product design. As a general rule, the assessment should be performed by a team of qualified SMEs who are generally recognized as an authority in a particular field by peers/colleagues and have the ability to interpret engineering design data, product manufacturing information (PMI), technical drawings, CAD drawings, described designs, prototype models and draw upon best practices. SMEs should expect to answer questions such as '*What are the critical aspects of the design?', 'How do the critical aspects of design interact with the aspects of manufacturing?', and 'What are the recommendations to improve manufacturability?'.*

MAKE Tool. The essential purpose of a manufacturability assessment for a product design is to provide a timely and comprehensive analysis by qualified SMEs in order to determine the relative ease (vs. difficulty) with which a product can be made. SMEs tasked with performing the assessment need an effective means of (1) accomplishing the review, (2) compiling the results, and (3) communicating the results. No currently available software provides that capability based on the uniqueness of the methodology.

In order to provide users of the MAKE tool with an efficient means of executing a manufacturability assessment of specified designs, the research team designed a custom software tool. The tool incorporates the structure of the assessment methodology created by the MAKE SMEs and designers. From a high-level perspective, the software tool should cover the three main areas of the assessment process (i.e. the E-D-P cycle), and include all supporting information, visualization and documentation of the results in each of these phases.

The current design of the MAKE tool allows the SME team to evaluate parts and assemblies as individual components or in a hierarchy of components (i.e. BOM). After the components for evaluation are set-up in the tool, the SME initiates the evaluation phase of the assessment process by scoring the component in accordance with the matrix described earlier in this report.

The entry screen contains best practice guidelines, definitions and comment areas so that the SME team can capture all the information needed for the assessment. Once all the components are scored, the assessment enters the diagnosis phase.

The visualizations from the MAKE tool provides the SME team with an overall snapshot of the assessment by component with focus on the aspects of design. This allows the SME team to understand which aspects of the design exhibit the most concern in the assessment. Depending on the level of concern associated with particular aspects of design, the SME team has the capability to deep-dive into that particular aspect of the design seeking to understand which aspects of manufacturing are driving the lower scores.

These results provide the SME team with some insight into each aspect of manufacturing and the magnitude of the concern in that particular area. Based on this information, the SME can begin to diagnose the details behind the lower scoring aspects of manufacturing to understand the drivers of design that are causing these low scores. Once this information is known, the evaluation enters the prescriptive phase where the SME team formulates recommendations associated with each area of concern and provides an evaluation for the customer on the amount of effort required to mitigate these concerns. Further application of this is explained in the following case study.

Case Study

This phase of the research involved a pilot case study on the application of the manufacturability assessment methodology on a military sub-system. By doing so, valuable information was obtained to 1) assist in understanding of the application of the methodology across various industries, and 2) gain insight into the effectiveness of the methodology in more complex product designs.

Background of the Case Study

This case study focused on the assessment of two products that are mostly electronic in nature. The goal was to use the methodology to help the client create a long-term strategy for increased production as well as possibly transitioning the current DoD product into a commercially manufactured product. Risk mitigation was a significant payoff to the customer as this was a complex system containing two major assemblies (product A and product B), 14 sub-assemblies, and 132 individual parts.

For the purposes of this paper, only examples from product A are included. Details for the complete case study can be found in the full working technical paper, (McCall, T., Walden, C., Dalton, L., et.al, 2017).

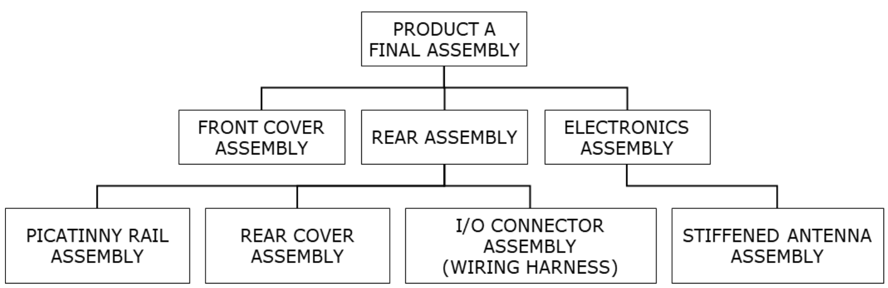
Application of the Methodology to the Case Study

To aid in the evaluation of this product, the assessment was broken into the following categories: Bill of Materials (BOM), Design Documents, Plastic Parts, Metal Parts, Electronics, Other Parts, Sub-Assemblies, and Final Assembly. The company had been developing this system for a number of years so a physical prototype was available for the team to perform a hands-on review and physical tear-down and re-assembly of the product.

The product consisted of two main assemblies; therefore, the team structured the assessment to perform separate evaluations of each assembly. Common components between the two main assemblies were only evaluated once to minimize any duplication of effort. The assessment of product A consisted of 25 unique parts, seven of which were sub-assemblies. The team did not perform an assessment on parts such as screws, nuts, and bolts because these parts were purchased off the shelf and did not pose a risk to the manufacturability of the product.

To begin the assessment, the team reviewed product documents including CAD drawings, bill of materials, and product specification sheets. Although a bill of materials was present for each of the products, an indented BOM did not exist. The team created this to aid in understanding the sub-assemblies that make up each of the products. Exhibit 3 shows the high level structured BOM the team created for product A.

Exhibit 3. BOM for Product A.



Product Design Documents. One of the first issues noted by the team was that the drawings were not dimensioned according to ASME Y14.5 for Geometric Dimensioning & Tolerancing (GD&T). Increased cost and/or delays may incur due to missing dimensions, lack of proper datum structures, over dimensioning or other concerns due to non-standard dimensioning practices.

Plastic Parts. The housing designs were assessed with numerous opportunities for cost savings noted. While the material for the plastic components was dictated by the customer (military), various design features of the housings required very costly mold tooling. Unfortunately, these costs were already incurred, so it was impractical to make changes that required revision of these tools.

Metal Parts. The metal components within the product exceeded the team's expectations on cost as well as manufacturability. The machine house provided quality finishing of the parts (on-machine deburring, good surface finishes, etc.) and reasonable costs for the low volumes being produced. The team recommended adjusting some of the radii and cutouts used on one particular part in order to provide cost savings and reduce the work involved to produce the part.

Electronics. The electronic boards were designed for compact, lightweight, and portable use. Thus, the design philosophy was to use a compact, dense population of components on multi-layer printed circuit boards. This made it difficult to find competent suppliers who were able to manufacture the circuit boards and assemble numerous miniature components. The combination of densely populated boards in low volume quantities led to significant quality issues resulting in low yield.

There is currently little in the way of testing of completed electronic boards prior to the final assembly. This concern was responsible for driving significant costs, in not only the replacement and scrap associated with very expensive boards but in the assembly process time as well. This has driven additional processes involving the pre-assembly of the units with temporary means of fastening, tear-down after testing, and re-assembly with permanent fastening methods for final assembly and testing. These additional processes are responsible for a significant portion of the costs but the expense of replacing the printed circuit boards have the potential to be a show stopper.

Miscellaneous Component Parts. The team assessed several other parts that did not fit into one of the aforementioned categories. Very few issues were found with these parts. One part was a sheet of adhesive used to hold a circuit board to a metal part. The team recommended using a spray on adhesive to eliminate the wrinkles that formed in the adhesive sheet when assembling this set of parts.

Sub-Assemblies. Currently, assembly of both products is done in-house. As part of the assessment effort, SMEs considered multiple manufacturing scenarios: assembly on-site by company personnel as well as off-site assembly at either a company owned manufacturing location or an outsourced manufacturing company.

During assessment of the sub-assemblies, the team noted that assembly drawings were clear with few discrepancies found between the drawings and the BOM. On the downside, apart from torque verification, no in-process testing was specified in the manual or on the drawings. This means the entire product has to be assembled before any testing is completed. Following this method, if a defect is found in the completed product, the product needs to be disassembled for a root cause analysis. Furthermore, the team was not able to find any references to quality, product or testing standards in the documentation provided.

As part of the manufacturability assessment, it is typical to also uncover issues that are solely manufacturing concerns and not associated with the product design. There were several areas where this occurred including: 1) lack of calibration records associated with the torque wrenches used in the assembly process, 2) lack of tracking mechanisms to confirm and record torque measurements for each product built, and 3) incorrect selection of the torque wrench size used for assembly. Suggestions were made to transition to digital torque wrenches or investigate use of torque-limiting wrenches. On a more positive note, the SME team found the assembly manuals to be quite detailed and served as a valuable source of information in the evaluation of the assembly process.

Final Assembly. In evaluating the assemblies, some principles for Design for Manufacture and Assembly (DFMA) were noted and best practices suggestions were made. Issues that were of a design nature were documented in detail as part of the assessment effort. Likewise, there were issues of a manufacturing technique and process that were documented with suggestions that should aid in the assembly process going forward.

One troublesome item the team encountered was the use of small metal screws, nuts and washers and metal stand-offs. The team provided recommendations for alternative stand-offs made of plastic that could replace the metal ones as well as eliminate some of the screws, nuts and washers.

Results

With the use of the MAKE tool and V2.0 of the MIM, assessments for each part and assembly were performed. Each part/assembly was rated using the rating scale in Exhibit 4. The resulting scores for one example are shown in Exhibit 5.

Exhibit 4. Concern Rating Scale.

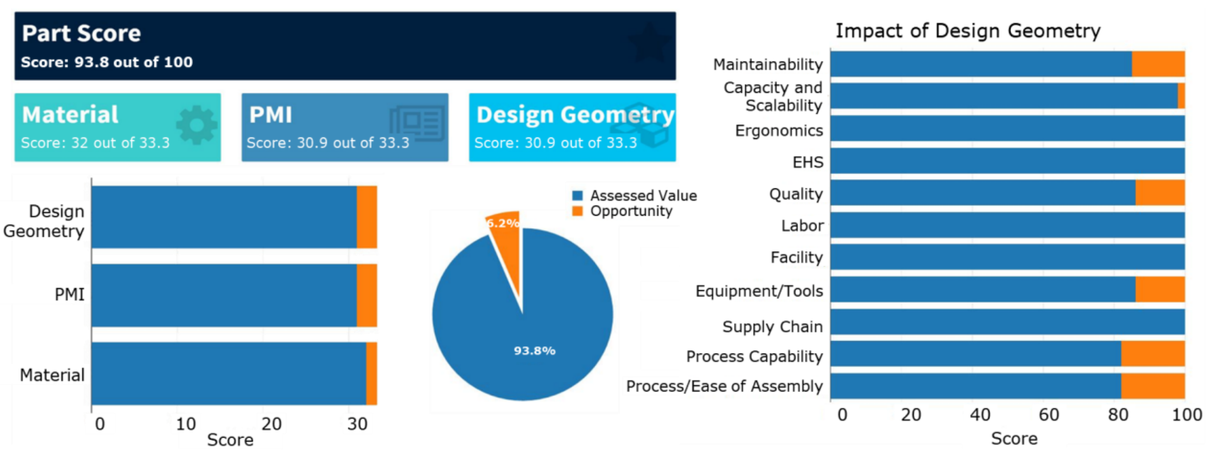
Rating	Description
1-60	High concern, significant issues, stop and evaluate
61-85	Medium concern, some issues (additional build time, extra resources, and special tooling, etc. may be required), proceed with caution
86-100	Low concern, very few issues, proceed

Exhibit 5. Scores for Product A Assessment.

	XXX-X00-X00.Material	XXX-X00-X00.PMI	XXX-X00-X00.Design Geometry
Process/Ease of Assembly	95	80	82
Process Capability	90	80	82
Supply Chain	100	100	100
Equipment/Tools	100	95	86
Facility	100	100	100
Labor	100	100	100
Quality	90	80	86
EHS	100	100	100
Ergonomics	100	100	100
Capacity and Scalability	90	100	98
Maintainability	90	85	85

Exhibit 6 shows the corresponding overview of the assessment. This visualization depicts slightly more concern with Design Geometry and PMI than Material. By focusing on the aspects of design with the highest concern (lowest scores), the SME team was able to drill down into those areas of concern.

Exhibit 6. Results from Product A Assessment.



As part of the assessment, the SMEs documented the particular concerns within the areas noted in Exhibit 6. Additionally, the SMEs provided recommendations associated with the findings or concerns. SMEs use their respective expertise, experience and demonstrated best practices as the basis for these recommendations. For example, designs that over-specify dimensional and/or surface finish requirements for geometric features (e.g. honing vs. standard machining) of a design can significantly increase processing costs (Anderson, 2014). Examples of the concerns and recommendations are shown in Exhibit 7.

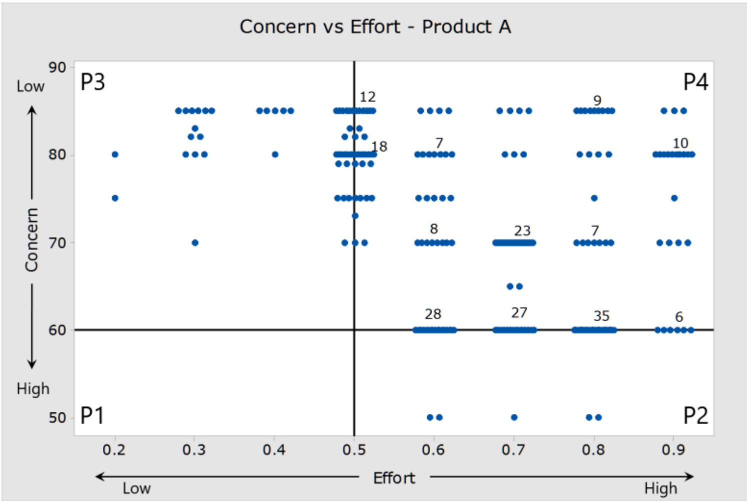
Exhibit 7. Example Concerns and Recommendations.

Category	Concern	Recommendation
Drawings	Excessive use of basic dimensioning •This drives up machining and inspection costs	Use basic dimensioning sparingly.
Drawings	Over dimensioning – too many three place decimals. •Three places decimals with +/- .005 in. This level of tolerance drives cost, if they are unnecessary.	Revise drawings as necessary to minimize these requirements.
Drawings	No critical to quality notations. •CTQ designations allow a reduced level of quality inspections	Provide a CTQ Code on the critical dimensions.
Metal Components	Material for the stiffeners is aluminum.	Recommend machining from plastic stock in the prototype and pre-production stages and changed to injection molded later when the production orders begin. Potentially results in lower cost.
Metal Components	Some features on the stiffeners can be modified to minimize machining time and reduce tooling required.	Small filet radii in some instances drive using a small endmill to form the feature, whereas the standard mill cutter could be used with more generous fillet radii. Multiple steps or cutouts are used when they may be extended to avoid multiple directional passes with a small tool.
Assemblies	Spacing of board components does not allow for the use of standard sockets. Standard socket appears to touch the resistor (see picture). 	1) Use thin walled sockets. 2) Specify and use sockets with protective coating.
Assemblies	Ribbon cable installs in both directions.	If orientation is critical to design intent, need to address the keying of the ribbon cable as poke-yoke to prevent mis-orientation of the ribbon cable.

The recommendations (i.e. improvement actions) associated with each concern were rated by the SMEs based on the anticipated effort to implement the action. Any recommendation with an effort to implement rating of 0.7 or above was considered difficult, effort ratings from 0.4 to 0.6 were deemed to be of medium difficulty, and ratings of 0.3 and below were classified as easy to implement. In summary, there were 228 concerns and 134 unique recommendations identified in the assessment of products A and B.

The concern and effort ratings were combined to create concern vs effort (CVE) chart to provide indication of the benefit vs. effort relationship associated with recommendations. Exhibit 8 shows the CVE chart created for product A.

Exhibit 8. Concern vs Effort Chart - Product A.



The research team chose to designate the dividing lines to delineate the high concern values (scores of 60 and below, y-axis) and the median effort rating (0.5, x-axis).

P1 represents the high concern/low effort values, which typically would be addressed first. P4 represents low concern/high effort values, which typically would be addressed last. Zones P2 and P3 may take on a different level of importance depending on company goals and available resources. A focus on improving manufacturability would drive the team to prioritize P2 over P3. Often times, limited resources within a company may drive them to prioritize P3 over P2, even at the risk of minimizing the improvement in the manufacturability of the product.

Customer Feedback

Out of the 268 total recommendations, the customer indicated they were likely to implement 141 immediately and 63 on a future revision of the product. The remaining 64 recommendations were not likely to be implemented due to requirements that could not be changed, expenses that had already been incurred, or inability to change the design. Therefore, out of the total recommendations, there was 76% agreement with the customer on future actions needed to improve the manufacturability of the product.

Conclusions

This paper has served to introduce the development of the Manufacturability Assessment Knowledge-based Evaluation and a taxonomy of key aspects of design and manufacturing utilized to perform the assessment. In addition, the paper introduces the MAKE assessment tool and presents the application of MAKE to a DoD case study.

The case study application detailed the approach of the assessment to a system level product design. The results of the case study served to illustrate the connectivity between various aspects of the system. From the case study details, the results indicated that 228 concerns were identified and led to 134 unique recommendations. Upon a close review, there is an interesting relationship between concerns and recommendations. In some cases, one recommendation addresses a broad range of concerns, in other cases several recommendations are needed to address a single concern. This may reflect the notion that a product design is an integrated system, and as a result, there appears to be a “Pareto effect” in terms of identifying a relative few of the recommendations that drive the majority of the improvement in manufacturability.

Implementation of this case study has resulted in the use of a taxonomy based software tool (MAKE) to identify pertinent factors that influence the manufacturability of a product design. When considering these factors in the context of a prototype or early production design, it is important to consider how this approach could be used earlier in the design life cycle when the design is less well defined. This is an important area for further research, since there is greater opportunity for impact earlier in the design cycle.

The review of the improvements to MAKE and its application to this case study provided additional insight into future areas of concentration within this research. Some of these areas include: 1) ongoing development of a global scoring metric to represent manufacturability of entire system/product design, 2) changes to the methodology to assess designs with less fidelity (i.e. conceptual stage), and 3) streamline of the methodology to improve the efficiency of MAKE.

This information will be used to frame future improvements to the existing methodology to create the next version of MAKE.

Acknowledgments

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