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DESIGN OF THE MANUFACTURABILITY ASSESSMENT KNOWLEDGE-BASED EVALUATION TOOL

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Abstract
The early stages of manufacturability design play a major role in the life cycle cost of a product, as such, there is a need for the application of systems level thinking and input from subject matter experts (SMEs) to be incorporated into early phase design decisions that will potentially impact life cycle costs. The literature shows that current tools available focus mostly on cost, with none focusing solely on early manufacturability and design. The Manufacturability Assessment Knowledge-based Evaluation (MAKE) is a tool created to aid SMEs in assessing the manufacturability and early design of a product. This type assessment is being created for the U.S. Army Engineering Research and Development Center's Engineered Resilient Systems program as an input variable.

This paper will document the research and comparisons of other Design for Manufacturability tools. The outcome of this research provides the foundation for the need for a new tool and methodology. Additionally, this paper will outline the research performed to build the requirements for the MAKE Tool, discuss the lessons learned from case studies that led to improvement in the tool, and present an overview of the MAKE Tool. It will also discuss plans for integrating best practices from industry and concerns and recommendations from SMEs. New capabilities are planned for the tool as research continues.

Keywords
Manufacturability, Tool, Subject Matter Experts, Design

Introduction
Acquisition experts for the Department of Defense (DoD) perform trade-off analysis of various system attributes, such as performance metrics, geometric information, and cost during the acquisition process. The Engineered Resilient Systems (ERS) program provides these experts with the capability to perform the analysis on much larger sets of design alternatives or options. In support of the ERS program, research is underway at the U.S. Army Engineer Research and Development Center (ERDC) to provide these experts as early in the acquisition process as possible attributes that, historically, are not available until very late in the process if at all. The Design for Manufacturability (DfM) was identified as one such attribute. There are many resources available to manufacturers and engineers such as guidelines, checklists, data sheets, software programs, etc. that focus on providing best practices for design and assembly of manufactured parts (Boothroyd, Dewhurst, & Knight, 2011). Most of the information available focuses on the DfM analysis of individual parts but does not cover other functional areas of manufacturing that impact cost, such as labor and ergonomics. These resources for manufacturing are also incorporated into a computer-based system for ease of assessing products.

The research to create a new manufacturability tool stems from the lack of a computerized tool that specifically looks at manufacturability and does not link directly to cost. The Manufacturability Assessment Knowledge-based Evaluation (MAKE) software application draws upon a taxonomy of manufacturability concerns, based on functional areas of a manufacturing system. It serves to identify areas within each manufacturing system that are impacted by characteristics of the design, as well as concerns that can be used to compare alternatives of a design. (McCall et al., 2018). The MAKE methodology is designed to accomplish two things. The first is a metric or value that represents the manufacturability of the product design and is the basis of evaluating or comparing various design alternatives. The second is the assessment portion of the methodology which provides feedback on how to mitigate concerns for future improvements to the manufacturability metric. Whereas the methodology has no direct correlation that can be applied to the metric to generate an overall cost of manufacturability associated with a product design, it does define concerns that are actual risks and/or cost drivers that could potentially impact the overall life cycle cost due to issues that may be encountered if recommended changes to the design are not made.

The MAKE tool, detailed in this paper, is the initial phase of research to provide ERS with metrics quantifying the design for manufacturability as input to the "Set Based Design" process of ERS. This set based design requires assembly of diverse inputs, models, historical data, and simulation into a single, large, trade-space of possible design options. A trade-space is a multi-variant, mathematical trade-off design space used to identify design possibilities based on optimal boundary spaces (Brantley, 2002) (Ross, 2004). Optimal boundary spaces could include numerous variants such as cost, mission performance criteria, engine horsepower/size, and manufacturability data. These boundary conditions are used to reduce the set of choices until the entire space of possibilities is more fully understood.

EDRC is developing the ERS tools that will be used for trade-space evaluations. ERS is used to build combat systems that are responsive to increasingly complex and dynamic military missions, as well as provide tools that significantly amplify design options during the early stages of the DOD acquisition process. Military tradespaces tend to be large datasets (on the order of 100+ columns by 1 million+ rows). Efforts are underway to include early lifecycle manufacturing data as a variant and the research team is researching the creation of an assessment software tool to aid in the collection of ERS variable input data.

Literature Review

A review of the literature indicated that there is a lack of published research after the 1990s on manufacturability assessment, scoring, and identification. In the article "A Multi-Criteria Model for Evaluating Design for Manufacturability" (Das & Kanchanapiboon, 2011) a Pro-DfM model analysis identified product realization opportunities for cost reduction. It focused on the geometrical features of the parts in the design, using models and a library of knowledge, and estimated the part production and assembly costs. The authors of this article, like the research team, realized the need for custom fitting best practices depending on the product being assessed. This article was unique in publishing the value of Subject Matter Expert (SME) knowledge within the tool. Das et al. felt that an effective DfM method should have the following features: utilize the manufacturability knowledge of the SMEs, integrate the manufacturability evaluation into the cost estimation process, use a multi-dimensional analysis with flexibility of focus, and provide quick evaluations that can be updated. The current software tools available are at each end of the spectrum and provide estimates of manufacturing cost, or use sophisticated tools that perform detailed design analysis and offer redesign suggestions. Das's tool used a 0 to 10 scale and was similar in structure to the MAKE team's tool, baring the fact that each interaction scored was linked to estimated unit production cost. This cost was divided into four categories: parts procurement, assembly and fabrication, inventory holding, and supply chain costs. Das's tool also included penalty factors for parts, assembly, fabrication, and inventory. The penalty factors were used to derive the estimated unit production cost. Their methods also relied heavily on their team's own manufacturability experience and assumed that a bill of materials, parts list, and assembly drawings were provided. The requirement of Das's model to have a complete bill of materials was a challenge the MAKE team sought to address and thus allowed the user to either incorporate a bill of material or create a bill of material from scratch before starting an assessment. The MAKE team does not require a completed bill of material as a stipulation for using the tool because past experience has shown that many products do not have completed documentation when this assessment is conducted.

In the article "Developing Manufacturing Response Models to Predict the Manufacturability of New Modular Products" (Salhieh, 2008), a manufacturing response model was proposed to model the behavior of the manufacturability as a response to the series of decisions made during the design process. Salhieh et al. proposed that the manufacturability of modular products should be understood in terms of three major factors; namely, the complexity and functionalities of the product being designed, the variety of the physical components chosen to perform the functions identified, and the process variety needed to produce the components. The authors used a provided set of rules within the tool created by SMEs. They concluded through research that the manufacturability of modular products is a direct response to the series of decisions made during the design process. Each major factor was calculated mathematically from SME inputs and data collected from existing product designs with known structures and manufacturability. Similar to the MAKE software tool, this method utilized a mathematical modeling approach for manufacturability along with SME inputs.

The goal of the research outlined in the article "Toward Rapid Manufacturability Analysis Tools for Engineering Design Education" (Lynn, 2016), was to teach students about how design can impact the cost of manufacturing through the use of a high-performance computing (HPC) accelerated parallelized trajectory planning software. This software allows students to visualize subtractive and additive manufacturing methods for designed parts. They used several factors for evaluating the manufacturability of a product using turning and milling processes. These factors included: build volume, minimum feature size, volume of support material, build time, estimation of surface roughness, and build orientation. This approach eliminated the steep learning curve associated with traditional manufacturing processes for new students through the software. The new framework provided a shortcut to engage in DfM without the startup cost and allowed them access to HPC. Utilizing HPC to evaluate results of the MAKE tool is a long-term goal of the research for the ERS project and Lynn's research shows how HPC is already being utilized in manufacturability systems.

In the article "An Improved Methodology for Evaluating the Producibility of Partially Specified Part Designs" (Aurand, 1998), a hierarchical evaluation methodology for early design (HEMED) was developed to address the need to estimate the downstream implications of partially specified part designs as early as possible in the design cycle. Similarly, the MAKE tool utilizes a hierarchical bill of materials to evaluate parts and assemblies. Aurand et al. found there was a need to provide more dynamic and context-dependent feedback regarding the producibility of piece-part designs. The methodology created rated the downstream effects of piece-part designs within a fixed-principle environment using a scale from zero to 100 percent. The HEMED methodology however, was limited to the aerospace industry and it was believed that unexpected challenges would arise when applied to new domains and improvements and modifications may be needed. Three significant contributions from this research were a taxonomy that organized the approaches and systems used previously, the creation of a new methodology for evaluation of the downstream effects of partially specified piece part designs, and the fully functional implementation of the HEMED methodology at one aerospace manufacturer. In contrast to the HEMED creators, the MAKE tool creators are striving to broaden the application of the tool so to better fit multiple manufacturing areas by using general scoring interactions and best practices along with giving the user the option to include specific to the product best practices.

Methods

The goal of this research is to create a manufacturability scoring methodology and MAKE software tool, which addresses key aspects of design and manufacturability without incorporating cost. Through the application of several case studies, it was recognized that cost was inherently part of each of the aspects of design and therefore did not need to be addressed separately. This could potentially cause duplication in the scoring of a part's manufacturability. The MAKE tool is not a replacement for the SME but instead is used to communicate guidelines for the assessment, ensure assessment occurs on all identified parts and assemblies, and identify and prioritize the activities needed to improve the resulting manufacturability score. The tool also allows the SME or assessor to identify key concerns and recommendations for each assessment for the benefit of the end users.

The software was developed as a Web-Service with the server-side software written in Python, using the Django framework. It encompasses both the Manufacturability Interaction Matrix (MIM), which focuses on the attributes of manufacturability that impact the design of a part or assembly, and the corresponding concerns and recommendations. Exhibit 1 shows the MIM, which answers the question "What is the impact of each aspect of design on a particular aspect of manufacturability?" Each interaction of the matrix is available to be scored by an SME on a 1-10 scale. Exhibit 2 displays the scoring guidelines included in the tool as a starting point for the SME to consider during scoring discussions. General manufacturing best practices are also available within the tool as an aid for SMEs. This ensures the information necessary to make manufacturability judgements is available during the assessment and helps to reduce any bias between assessors. Process specific best practices can be inputted by the SME. These specific best practices can then be added to the pre-existing general library.

Exhibit 1. Manufacturability Interaction Matrix (MIM).

Aspect of Design (AD) → / Aspects of Mfg (AM) ↓	Material	Product and Manufacturing Information (PMI)	Design Geometry
Process	X	X	X
Quality	X	X	X
Supply Chain	X	X	X
Capital Tooling & Equipment	X	X	X
Labor	X	X	X
EHS & Ergonomics	X	X	X
Capacity and Scalability	X	X	X

Exhibit 2. Scoring Guidelines Included in MAKE Tool.

SCORING GUIDELINES FOR MAKE

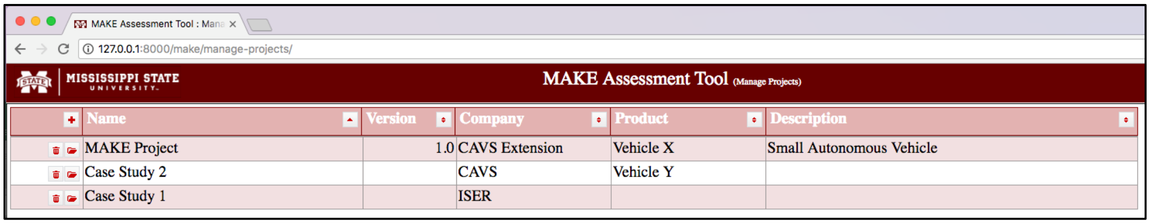
Impact of Interaction on Manufacturability - As determined by Subject Matter Expert (SME)	Rating	Color Scale
Minor: - No significant impact identified by the SME. - Concerns are minor and unnoticeable to the customer. - No impact to product yields.	1-2	
Low: - Slightly significant impact predicted by SME. - Concern may cause slight customer annoyance. - Slight deteriorization of the product or service, minimal impact to the next process or minor rework. - Moderate facilitative efforts can be expected to maintain required production levels.	3-4	
Moderate: - Moderately significant impact predicted by SME. - Concern identified may result in customer discomfort and dissasfaction. - May cause the need for unscheduled repairs or rework of the product. - Production yields may be significantly less than required due to one or more quality, delivery, or efficiency performance issues.	5-6	
High: - High degree of impact predicted by the SME. - Concern will result in high customer dissatisfaction due to the nature of the failure such as an inoperable product or process. - Does not involve safety issues or government regulations but will cause the need for unscheduled repairs or rework of the product. - May cause disruptions to subsequent processes with high impact to production yields.	7-8	
Very High: - Very high impact to manufacturability predicted by the SME. - Concern involves loss of primary functionality with very high impact to the customer. - Concern may involve safety or regulatory issues. - Production yields are significantly impacted with significant repairs, rework and retesting required.	9-10	

The initial version of the tool was created and used as a method of testing both methodology and usability and was a point of discussion in the 2017 ASEM conference paper "Manufacturability Assessment Knowledge-Based Evaluation (MAKE) and a Pilot Case Study" (McCall et al., 2017). After the conclusion of two case studies, it was apparent this version required improvements in the areas of saving assessments, re-using assessments, scoring adjustments, and general usability for the assessor. Additionally, the graphical user interface was improved along with the tool's ability to provide outputs from the assessment in standardized tables, charts, and summary sheets.

Tool Overview

Exhibit 3 shows the user's view upon logging into the tool. A list of projects, the version, company, and description information for each project will be presented as well as the ability to create a new project.

Exhibit 3. Project Creation Page.

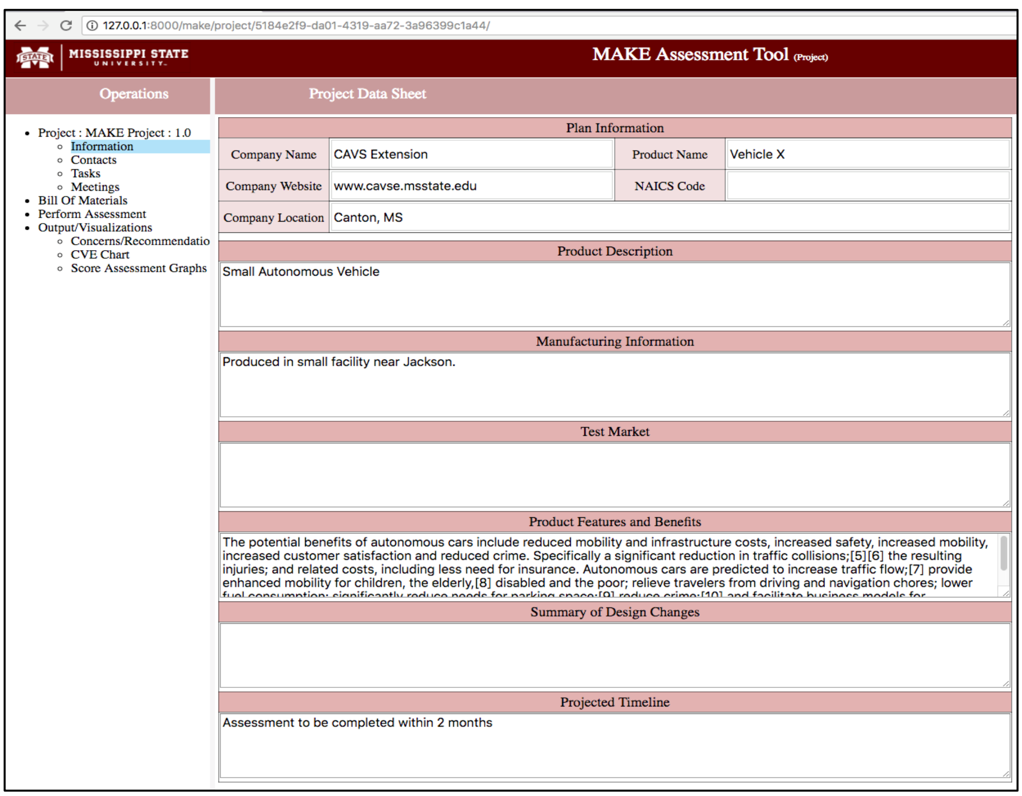


After the user selects a current project or begins a new one, a divided interaction space appears. The far-left section houses the Operations, the center section houses Project Details and the Bill of Materials (BOM) in hierarchal structure, and the right section is where the user inputs data. Each section also has an export option that allows the user to export the displayed information. This is especially helpful when the assessment team has to create a BOM for a customer. The exported BOM is another product for the customer, along with the assessment results.

Operations

Under the project bullet, the user is able to add information related to the project, see Exhibit 4. Additionally, contact information for customers, tasks for team members, and meeting information can all be included. Light blue areas indicate editable input space and additional rows are added when the plus button is clicked. Similarly, changes can be cancelled or saved by clicking the respective icons on each row.

Exhibit 4. Project Data Sheet.

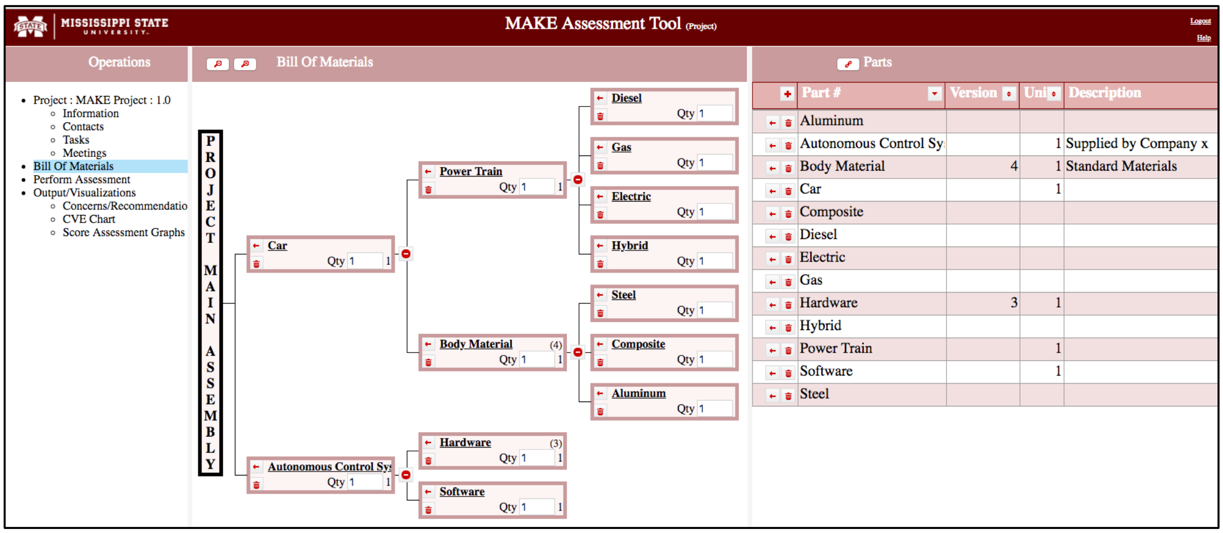


Bill of Materials

If a leveled or indented BOM is imported, a tree diagram will automatically populate in the center pane. If a BOM is not available, the user can add parts to the right side of the screen. After creating the part list, the BOM structure can be created. If only a list of parts is available, the structure can be created after importing the list. Once created, the BOM structure is editable.

Looking at Exhibit 5, the selected parts on the BOM structure are indicated by a black outline. To add children to a part, select the parent part on the structure and click the arrow button for the desired child from the parts list to the right. If the child part does not exist in the parts list, click the plus button to add a new part. Once the users have input the necessary information for the child and clicked save, indicated by a folder button, a new box will appear connected to the parent. This action will apply across the entire structure and will add the same child to the identical parent on all parts of the diagram.

Exhibit 5. Bill of Materials Creation.



Red circles located along the connecting lines on the tree will allow the user to collapse or expand the children of a parent part for ease of viewing purposes. Within the individual part boxes on the tree, there is a quantity box to indicate the number of parts needed at this point in the BOM and a delete button. If a part is deleted from the tree directly, it will only remove it from the tree. The part remains in the master part list in the right column.

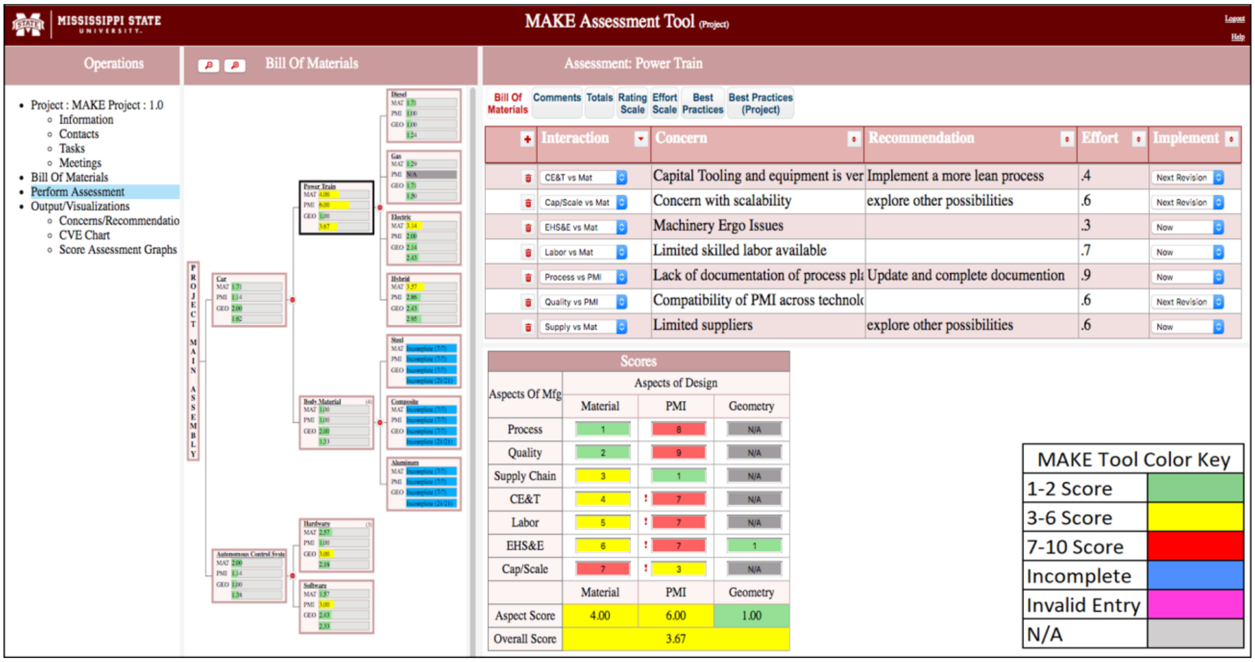
The bill of materials can be exported into an Excel file from any position on the tree diagram. To export the entire BOM, select the project main assembly box on the graph. To export a portion, select the starting point parent and click the “Eexport” button. This will export the BOM from the parent selected down.

Perform Assessment

The Perform Assessment page is where the user will document concerns and recommendations, create scores based on those concerns, and rate the expected effort to implement the recommendations. The buttons in the right column allow the user to view the BOM, Comments, Totals, Rating Scale, Effort Scale, Best Practices, and Project Best Practices. If an interaction is scored at 3 or higher, the tool will flag the user to document a concern. Autofill features have been included in the text editable boxes and will recognize unique words to aid in the completion of concerns and recommendations for each interaction.

Rather than quantity of parts, the tree structure now shows the scores for each aspect of design within the part box. These graphs will update as scores are entered into the matrix and will show via the color scheme shown in Exhibit 6 if the part is completed, incomplete, or has an invalid entry. Any interaction can be voided from consideration in the scoring matrix by imputing a “N/A”. Each part has an opportunity for 21 scores across the different interactions.

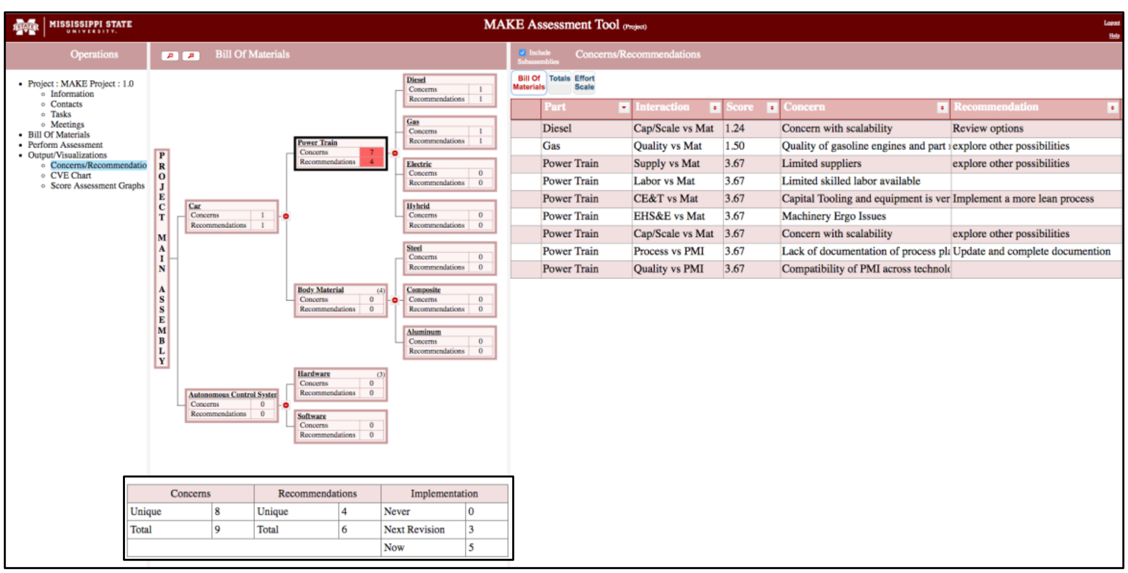
Exhibit 6. Perform Assessment Page.



Visualizations

Once an assessment has been completed, the next challenge is summarizing the concerns and recommendations and presenting the data in an easy to understand, actionable format. As shown in Exhibit 7, the tree diagram now shows the number of concerns and recommendations per part. The right side of the screen lists all concerns and recommendations for the part selected. Multiple parts can be selected as well. Additionally, the user can click the option to include children, which will compile the concerns and recommendations for the selected part as well as all of the follow-on parts. Red colored totals on the BOM indicate that not all of the concerns have been given a recommendation.

Exhibit 7. Concerns and Recommendations Summary Page.



In addition to summarizing the concerns and recommendations, Exhibit 8 shows the Concern vs Effort chart (CVE) that can be displayed. This will aid the client in understanding which issues should be addressed first as well as which issues have greater impacts. The size and color of the circles indicate if the recommendation will solve multiple concerns. The larger the circle, the more concerns are solved by the one recommendation. If a circle has a red boarder, it indicates that additional recommendations share the same concern rating and effort to implement score. A user can click each circle to see the associated sconcerns and recommendations.

Exhibit 8. Concern vs Effort (CVE) Chart.

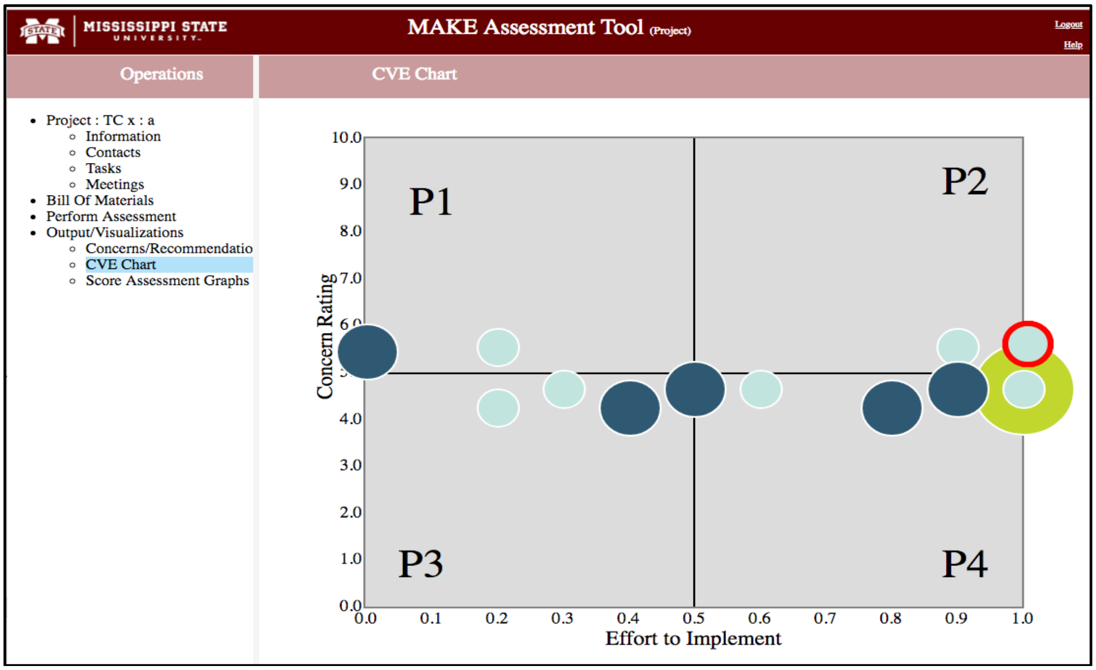
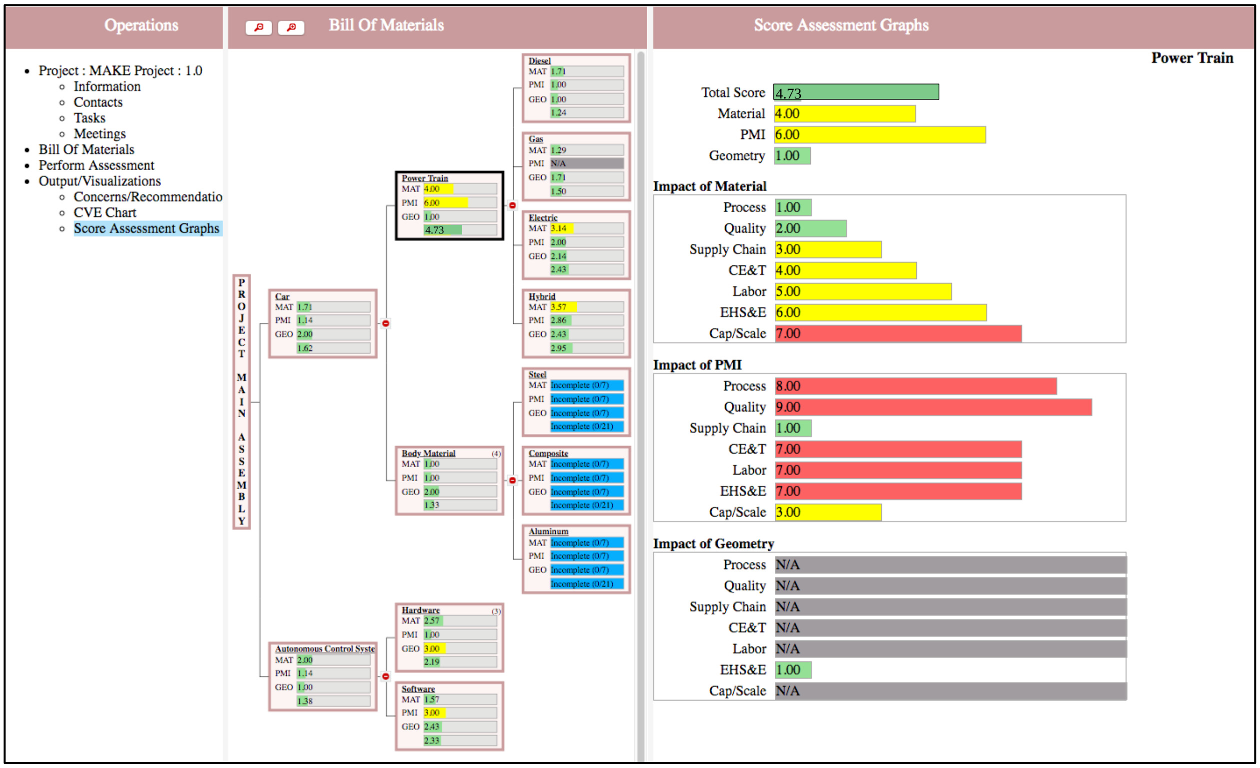


Exhibit 9 shows the final set of visualizations, the Score Assessment Graphs. When a part is selected, the right portion of the screen will display the individual scores for each interaction as well as a final score, following the color scheme previously discussed. For example, Exhibit 9 show the scores for the Power Train. The final score for this individual component is the average of the interaction scores equaling 0.73. These graphs can be exported for reporting purposes.

Exhibit 9. Score Assessment Graphs.



Conclusions

The purpose of the MAKE software tool is to provide for a timely and comprehensive analysis, by qualified SMEs, in order to determine the relative ease (vs. difficulty) with which a product can be made as well as identifying the concerns and recommendations needed to improve the product. The benefits of such a tool include not only a means for identifying risk and potential cost drivers within a product, but also could be used as a tool to aid in early design development of a new product. The researchers interested in developing a new methodology for determining the manufacturability of a product realized the need for a tool as an effective means of accomplishing the review, compiling the results, and communicating the results effectively. No currently available software provides that capability based on the uniqueness of the methodology. Therefore, in order to provide assessment teams with a user-friendly, effective and efficient means of executing a manufacturability assessment, the research team envisioned the presented custom software tool. The current version described will continue to be a standalone version used by the research team. The team is considering using the tool for future case studies with local manufactures. Ultimately, the tool or individual software modules of the tool could be extracted for use in larger, enterprise-type systems, such as ERS.

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