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MANUFACTURABILITY AND THE PRODUCT DESIGN: CASE STUDY EXPLORATION OF MANUFACTURABILITY ASSESSMENTS ACROSS A PRODUCT LIFE CYCLE

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Abstract

The challenge in the workplace with delivering high quality products to market in a timely manner has become increasingly more intense due to changing customer demands and expectations. The importance of incorporating manufacturing input earlier in the design cycle has evolved into a more common place concurrent engineering practice in order to minimize risk to performance, cost, quality, and schedule. However, there still remains the challenge of how to evaluate significant numbers of design alternatives during early stages of the life cycle acquisition process.

There is continued interest by the Department of Defense (DoD) on the assessment of manufacturability as part of the Engineered Resilient System (ERS) effort as they develop new military systems. Prior research has led to the development of a Manufacturability Assessment Knowledge-based Evaluation (MAKE) which is a methodology developed to assess the manufacturability of a product at various stages of a product's life cycle. At the foundation of MAKE is a taxonomy based on a matrix-style assessment designed to capture the impact of design decisions on the manufacturability of a product. This research paper discusses the development of this matrix, and its evolution and application in the manufacturability assessment process. Three case studies will be used to demonstrate the application of the taxonomy at several different points in a product's life cycle, as the research moves "to the left" toward an early concept phase where design fidelity is extremely limited.

Keywords

Manufacturability, Assessment, Metric, Life Cycle, Taxonomy, Design for Manufacturability, Product Design

Introduction

Development of products for both industrial and government applications is fraught with challenges. One of those challenges involves the ability to identify manufacturing issues early in the product life cycle prior to finalization of a design that may have inherent concerns that negatively impact the cost of the product over its life cycle. This challenge is of particular interest to the DoD, where investment is high and product life cycle can extend over a period of decades. Understanding of how to mitigate the manufacturability risk early in the design development is key to the Engineered Resilient System (ERS) Tradespace efforts involving research of the "ilities" and development of predictive methodologies, algorithms, or models to understand how these "ilities" impact the overall life cycle cost and contribute to the resiliency of combat systems.

The traditional approach to design for manufacturability (DfM) revolves around a few central points. The need to design products with the manufacturing environment in mind, resulting in products with low manufacturing cost, high quality and that meet the customer demands. To this end, there is an abundance of DfM information available to design engineers in the form of guidelines, checklists, data sheets, software programs, etc. (Bralla, 1996; Anderson, 2014; Boothroyd & Dewhurst, 1994). All of which are focused on providing design engineers with the best practices or rules-of-thumb necessary to design parts and assemblies with a focus on manufacturing. Rather than design engineers basing their decisions on traditional form, fit and function, DfM adds another layer of complexity for trade off analyses associated with the design.

Most of the information available in the DfM community is focused on the DfM analysis of individual parts and assemblies by identifying characteristics of the parts or assemblies that may cause issues during the intended manufacturing process (i.e. machining, casting, welding, assembly, etc.). In most cases it does not extend to other functional areas of manufacturing that have impact to manufacturing cost, such as the labor involved with training for new or specialized processes, environmental, health and safety (EHS) concerns that may drive the need for special equipment or training (McCall, et al., 2018).

The Manufacturability Assessment Knowledge-based Evaluation (MAKE) "draws upon a taxonomy of manufacturability concerns (i.e. life cycle cost drivers)", based on a manufacturability interaction matrix (MIM) (Walden, McCall & Gedik, 2016). This paper will focus on the development of the MIM and the changes in the taxonomy as a result of the application of this methodology to pilot case studies.

Literature Review

Concepts associated with design for manufacturing date back to the early 1900s, but became more prevalent and formalized in the 1960s with such methods as Hitachi Assembly Evaluation Method, Boothroyd & Dewhurst Design for Assembly (DFA), and Lucas DFA Methodology. The work by Auran, Roberts, & Shunk (1998) provided a summary of the various design evaluation systems throughout the literature. A significant number of these systems are focused on identifying design concerns associated with manufacturing features (i.e. part geometry). McLeod (1989) introduced an empirical system to rate the "producibility of partially specified part designs" which utilized Producibility Assessment Worksheets (PAW) to assess the part design. However, like other design evaluation systems, it required detailed part drawings or some level of part detail to rate the probability of success (PS) that represented the metric for McLeod's rating system.

The information provided by Boothroyd and Dewhurst focused on identification of Design for Manufacturability and Assembly (DFMA) guidelines and practices associated with multiple areas of manufacturing processes from manual assembly to harness assembly to more common material processes such as machining, injection molding, and casting (Boothroyd, Dewhurst & Knight, 1994). Ultimately the focus involved utilization of these guidelines and mathematical equations to arrive at approximations to manufacturing costs. To that end, Boothroyd and Dewhurst extended this methodology to their software, DFA Product Simplification, which requires the availability of detailed design information with regards to the parts and assemblies being evaluated.

Shetty and Ahad's research involved the use of rating factors for DFA and Design for Disassembly (DFD) focused on several aspects identified in prior research. Boothroyd & Dewhurst and Lucas DFA serve as the basis for the DFA assessment while AR^3T^3 (Access, Removal, Reuse, Recycle, Tool, Task and Time) is the basis of the DFD analysis (Shetty & Ahad, 2015). The scope of this software tool involved only assembly type operations. Manufacturing processes for part formation such as machining, casting, molding, etc. were not considered. As with most evaluation tools, the resultant rating factors were used to highlight potential areas of redesign to be addressed by the design community.

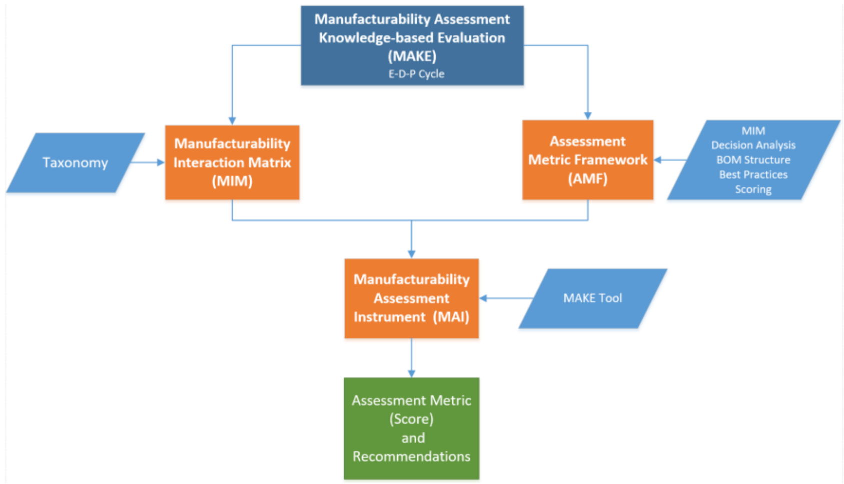
The research by Barbosa and Carvalho utilized the idea of tables to be used as checklists to provide guidance to design and manufacturing engineers (Barbosa & Carvalho, 2013). Each of the twelve tables focuses on a particular area of the design intended to be used during the product development phase. DFMA areas such as identifying the possibility of part number reduction, addressing accessibility and ergonomics issues, and ensuring that the drawings accurately identify the technical needs and specifications were just a few of the areas covered by the tables developed by Barbosa and Carvalho. While the research addressed guidelines outside the scope of what is typically involved with part fabrication or the assembly process, it did not involve the use of a metric or rating in which to compare design alternatives. In addition, similar to the work by others in the field, the tool required a certain level of design fidelity to assess the part or assembly in question.

While the information detailed in this section does not represent an exhaustive literature review, the information detailed thus far points to the availability of extensive design evaluation methods and tools. However, the majority appear to be based upon the availability of detailed design information. Since the ultimate intent behind DFM is to realize the manufacturing and assembly issues early in the product life cycle for mitigation of both cost and risk, there still exists the challenge of how to assess design for manufacturability at the conceptual stage of the design development at a level of depth that considers the holistic view of manufacturing.

MAKE and the Development of the Manufacturability Interaction Matrix (MIM)

MAKE serves to identify areas within each manufacturing system (Quality, EHS, Supply Chain, etc.) that are impacted by characteristics of the design. The concerns identified in the assessment drive the determination of a manufacturability metric than can be used to compare alternatives of a design at any level from the individual components up to the final assembly (McCall, et al., 2018). Exhibit 1 shows the general structure of MAKE (McCall, Fuller, Dalton & Walden, 2017).

Exhibit 1. General Structure of the MAKE Methodology.



Research by McCall et al, (2017) defined the Manufacturability Interaction Matrix (MIM) as "a taxonomy based system used to classify the key criteria of manufacturability" that "serves as the basis for the assessment and is used to provide a structured process for evaluating parts and assemblies within a given design."

Initial Development and Application of MIM, Version 1.0

While the MIM represents only a portion of the methodology, it is the foundation of the assessment taxonomy. The most appropriate questions in the research of a literature-rich area such as manufacturability involves the following:

- Where do you start?
- How can you add to the body of knowledge in this area?
- How can you develop a concept that is mired in the use of detailed design information and develop a metric for use in trade off analysis of early design concepts.

In the case of this research, the answers lay in defining the methodology around what was known and utilizing those insights gained in the process to move the assessment "to the left".

Prior research detailed the original approach in the development of the taxonomy which involved the use of affinity exercise and assistance by Subject Matter Experts (SMEs) to identify and categorize elements of manufacturability (Walden et al., 2016). However, these elements representing cost drivers or technical risk, could be classified in more than one manufacturing category. The interdependencies identified between the elements and categories prompted additional consideration into the system level connections found in the manufacturing environment. Instead of forcing these elements into categories, the researchers chose to embrace these interdependencies in the form of an interaction matrix. Within this matrix, the product design is evaluated based on the interaction of the "aspects of design" against specific "aspects of manufacturing". These thoughts were further reflected in the guiding question behind this assessment, "what is the impact of a particular aspect of design on a particular aspect of manufacturing?". Each interaction, X, shown in Exhibit 2, denotes a judgment made by an SME based on this guiding question.

Exhibit 2. Initial Basis of Taxonomy, MIM V1.0

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	

Case Study 1 – Rotatable TV Mount (RTVM)

Application of MIM V1.0

The first application of the matrix involved the assessment of a rotatable TV mount design. The details of this case study are covered in prior research (Walden et al., 2016). In essence, the MIM was used to systematically evaluate designated parts and assemblies within the product Bill of Material (BOM). For each part and assembly, the interactions, X, were given a judgment of high, medium, or low risk for manufacturability concerns. Based on a weighting system, these qualitative judgments were translated into quantitative scores. Rationale for each of these scores in the forms of a detailed concern from the SME was provided along with subsequent recommendations for prescriptive measures. While the initial case study allowed the researchers the opportunity to exercise the research methodology, there were several notable key outcomes. One of which involved the improvements needed in the MAKE taxonomy.

Lessons Learned

The current MIM includes 101 individual judgments of the interaction between the aspects of design and aspects of manufacturing that the SME must make for every specified part and/or assembly within the assessment. With a total part of 14 and assembly count of 6, the RTVM case study was categorized as a small content assessment. Even so, this still resulted in 2,020 individual judgments resulting in 300 scores for all the assessed areas (14 parts and 6 assemblies). Therefore, significant time was spent in the assessment of a small case study which translated to a large impact on time and effort given that the overall research intent is to be able to apply to the assessment to complex structures, such as military vehicle systems. This was found to be unrealistic given the time most engineering teams have available to assess manufacturability of the system design. The impractical nature of these findings prompted deeper evaluation of the observations noted during the assessment that would provide an avenue to reduce the size of the MIM. Some of these observations included:

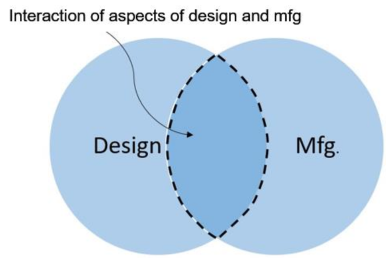
- Redundancy in the aspects of design resulting in duplication of the judgments. Design, part geometry, part dimensioning and material are all aspects of design, however, there is redundancy between them that caused similar concerns to be evaluated in different aspects of the design.
- Concerns on whether all of the defined aspects of design apply to both the parts and assemblies within the assessment. There were aspects of design that did not apply at the part level (e.g. Ease of Assembly) and aspects of design that did not apply to the assembly level (e.g. Strategic Sourcing) without qualifying information. Due to the inherent difference between the manufacturing processes involved with (1) making a "part" (e.g. from raw material) and (2) "assembling" multiple components, it would be beneficial to further refine the current assessment matrix, while considering the differences in these processes.

Since the current set of aspects of design resulted from an affinity exercise considering all possible manufacturing process scenarios, they were intended to be comprehensive and generally applicable across a broad spectrum of manufacturing processes. While conducting the RTVM prototype assessment, the subject matter experts noted that when assessing either a part or assembly, some aspects of design and associated aspects of manufacturing were not applicable and therefore did not contribute to the assessment results. The presence of "unused" or "unnecessary" aspects of design in the assessment instrument were somewhat confusing and increased the elapsed execution time for the assessment.

In addition to the above observations, it is well documented that reliability, maintainability, and sustainability are all significant criteria in the scope of engineered resilient systems. However, their individual connection to manufacturability was not explicitly obvious. Through reexamination of their definitions, the impact of reliability and sustainability may be more of a function of the design than any dependence on aspects of manufacturing (McCall, Walden, et al., 2016).

One of the most important discoveries regarding MIM, V1.0 was the lack of true separation between the aspects that belong in the category of design versus those that belong in the category of manufacturing. By evaluating the current MIM against the rationale associated with the Venn diagram shown in Exhibit 3 (Dalton, McCall, Walden & Watson, 2016), the researchers were able to formalize the matrix so that it accurately represented the true relationship between design and manufacturing.

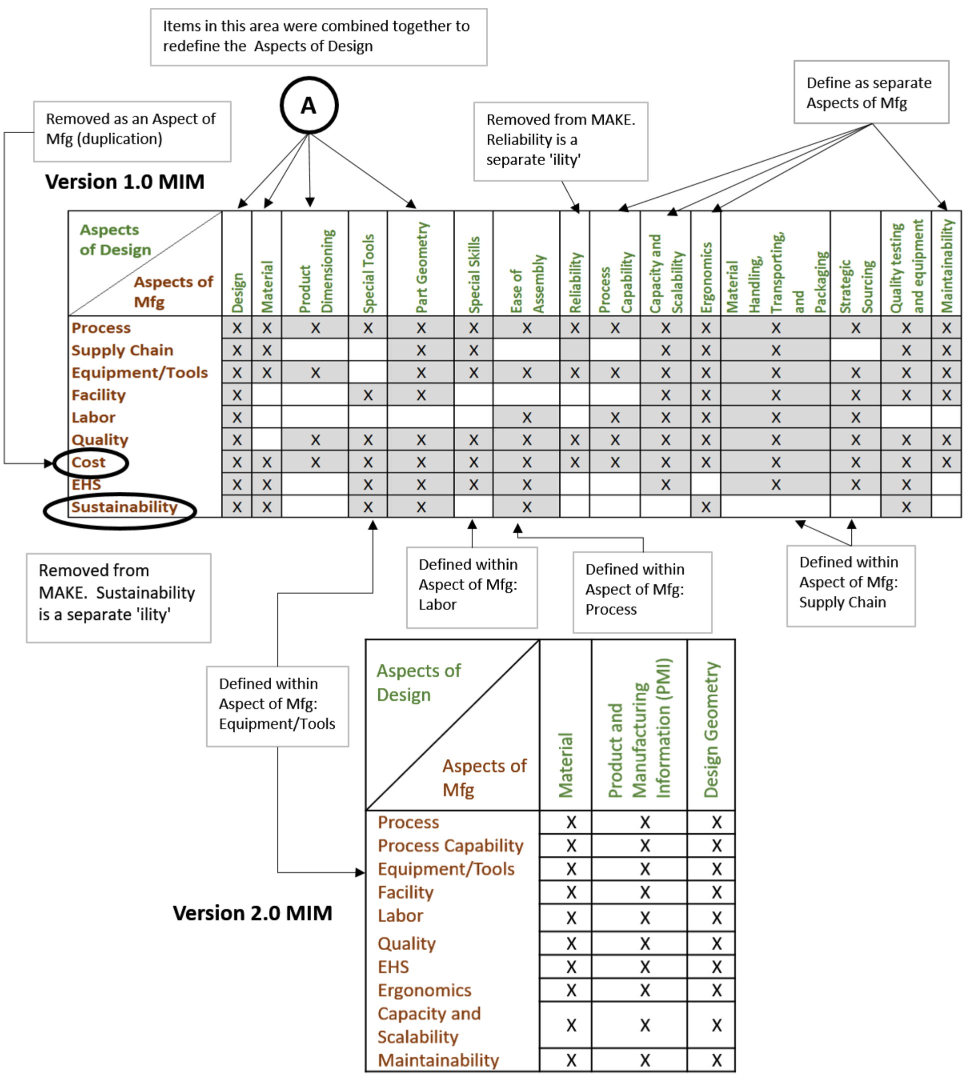
Exhibit 3. Venn Diagram Illustrating Manufacturability.



Development of MIM, Version 2.0

Prior lessons learned from the application of MIM V1.0 were used to systematically evaluate and reduce the size of the matrix resulting in V2.0 of the MIM (McCall, Walden, Dalton, et al., 2017). Exhibit 4 provides some background into the evolution of the matrix based on observations from the RTVM case study.

Exhibit 4. Evolution of the MIM from V1.0 to V2.0.



A significant modification came by way of reducing the size of the matrix from 15x9 to 3x11 and the number of interactions to be evaluated reduced by 67% (101→33) thus providing the benefit of improving the time and efficiency of the assessment. This reduction in size came from several modifications detailed in Exhibit 4.

One particular item to note was the removal of cost as an aspect of manufacturing. Although cost is a major factor in the assessment of the manufacturability of a product, it was implicitly evaluated at each interaction causing the evaluation of cost as a separate aspect of manufacturing to redundantly impact the assessment. For this reason, cost was removed from the matrix.

The final change to the matrix focused on the aspect of design. These aspects were reduced significantly and categorized to reflect typical design parameters. While most design information can be expressed in the form of product manufacturing information (PMI) and design geometry, the importance of the material aspect of PMI was considered to be of considerable significance to manufacturability. Thus, it was extracted from PMI and treated as a separate aspect of design. The final MIM V2.0, shown in Exhibit 5 is the result of improvements made to MIM V1.0. This version of the matrix allows for clearer understanding of the overlap between design and manufacturing and more accurately represents the guiding question, "What is the impact of the design on particular aspects of manufacturing?".

Exhibit 5. MIM V2.0, Second Iteration of the Iteraction Matrix.

Aspects of Design / Aspects of Mfg	Material	Product and Manufacturing Information (PMI)	Design Geometry
Process	x	x	x
Process Capability	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

Case Study 2 – Electronic Product for DoD Usage

Application of MIM V2.0

The second case study involved the application of MIM V2.0 and other improvements to the MAKE methodology to a DoD based product. The product targeted for case study evaluation consisted of two main assemblies; therefore, the team structured the assessment to perform separate evaluations of each assembly. However, 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. Product B consisted of ten unique parts, including five sub-assemblies.

With the use of version 2.0 of the MIM, assessments for each part and assembly were performed. One important differentiation from the prior assessment included the use of numerical scoring for each interaction as opposed to high/med/low judgments used in the first case study. The assessment team rated each part/assembly according to this new rating system with regard to perceived impact on the manufacturability of the final product. The results of this case study including the manufacturability scores, identified concerns and recommendations are discussed in prior research (McCall, Fuller & Dalton, 2017).

While the goal of each case study involved the benefit that the assessment provides to the customer, the secondary benefit is to the research and its cycle of improvements based on upon lessons learned at each application of the methodology. The observations and corresponding lessons learned in the application of MIM V2.0 to the case study are covered in the next section.

Lessons Learned

One of the observations in the use of MIM V1.0 was the perceived duplication of judgments. Upon closer evaluation, the duplication was less about the scores but more about the concerns that were driving the scores. For a single part or assembly, the number of repeated concerns identified at multiple interactions was seen as a potential duplication of effort. However, as the team reviewed this in more detail, one particular idea was considered. What if the notion of repeated concerns is just a key indicator of the breadth of the problem from a system perspective (McCall et al., 2017)? Considering the interactions within the matrix, one could easily see that a particular design issue could have impact to various aspects of manufacturing. For example, a certain feature of the design may affect the assembly process. This feature may make it difficult for the technician to assemble the two parts which could result in 1) increased labor inefficiency (refer to: labor aspect) or 2) increased effort used to assemble the parts (refer to: ergonomics aspect), or 3) a defect caused by forcing these two parts together (refer to: quality and process capability aspects). This problem may be an issue due to the materials chosen, the geometry of the design, or even the tolerancing of the parts (PMI).

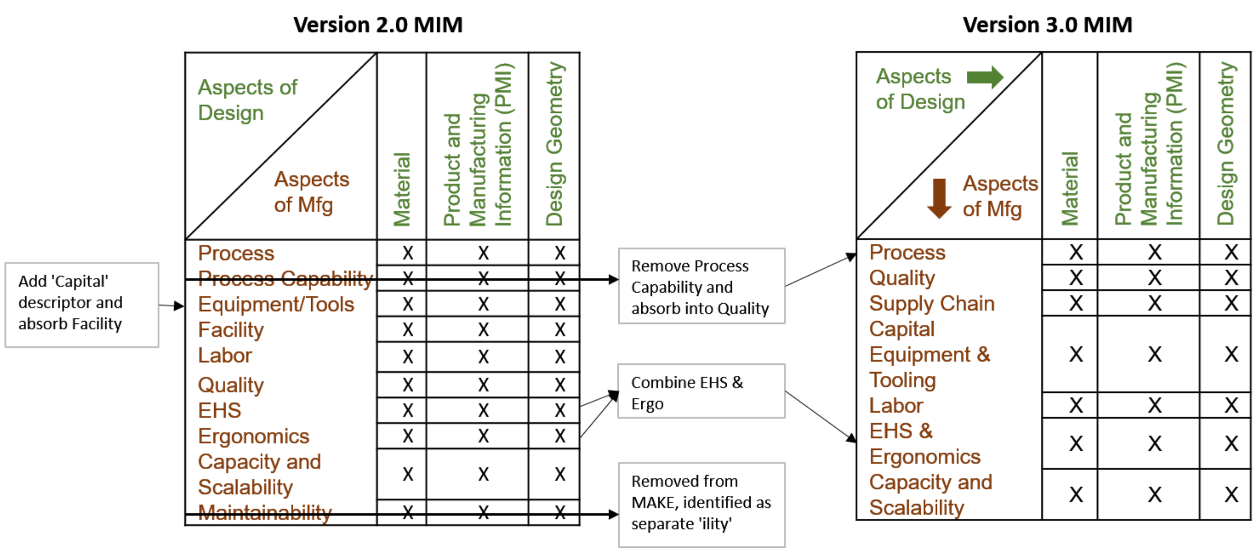
Another issue observed in the case studies was that in some instances, there was not enough information available for determination of the rating for particular interactions. This may be a common occurrence when the assessment is performed early in the product life cycle where certain details about the design have not been established or when the assessment is performed by a 3rd party where all information about the product may not be available to the assessment team. In this particular case, the latter represented the challenge of this case study. However, there is a need to account for these types of circumstances during the assessment. When an interaction cannot be scored, a "0" score is used, meaning not applicable. That interaction is removed from further scoring calculations, effectively rendering the interaction "mute" for that particular assessment. The methodology itself involves a cycle of assessments, meaning the manufacturability is evaluated at different stages of the product life cycle as the design becomes refined in preparation for production. As such, the methodology should accommodate stages in which fidelity of the design is minimal and provide a mechanism to evaluate manufacturability without the need for design details that are unknown at the time of the assessment.

As with the prior lessons learned, there still remained some overlap or duplication due to the categorization of the aspects of manufacturing. For example, process capability was identified as a separate aspect of manufacturing, however, due to its statistical nature most practitioners view process capability as more of quality measure. At times, the questions asked about the interactions with design and process capability may be similarly addressed in the interactions between design and quality. Subsequent aspects of manufacturing were evaluated in the same manner serving to further simplify the MIM.

Development of MIM, Version 3.0

In the application of MIM, V2.0 to the case study detailed by McCall et al. (2017), the researchers observed continuing areas of duplication and overlap within the matrix resulting in impact to time spent and concern with consistency in the evaluation. As a result, these identified areas were analyzed to determine ways to improve and reduce the size of the matrix. The modifications to V2.0 are shown below in Exhibit 6.

Exhibit 6. Evolution of MIM from V2.0 to V3.0.



The resulting improvements were driven by the need to construct clearer boundaries and establish more robust definitions for the aspects of manufacturing in order to prevent duplication in both the assessor thought process and in the scoring. The exclusion of maintainability is one that has been a major point of discussion for the team. However, the ultimate decision rested in the understanding that the application of maintainability was better addressed in the areas of sustainability.

As a result of these changes, the MIM was reduced from a 3x11 to a 3x7 matrix, reducing the number of judgments required by the SME from 33 to 21 (36% reduction). Exhibit 7 depicts MIM Version 3.0.

Exhibit 7. MIM V3.0, Third Iteration of the Interaction Matrix

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

Case Study 3 – Utility Box for DoD Usage

Application of MIM V3.0

The last case study was performed on redesign of an existing product. The research team began working with the designer in an active stage of their early development efforts. Due to the fact that this particular product used the rotomold process for fabrication, the research team was afforded the opportunity to apply MIM V3.0 to a unique manufacturing process as well as to a product in the early development phase.

The methodology within the MAKE involved the utilization of the MIM, best practice templates, and SMEs in performing the assessment. For this particular case study, improvements to the MIM were made as discussed in previous sections of this paper. This case study was used to illustrate that the streamlined MIM was still effective in assessing the manufacturability of a product. In addition, the flexibility of the matrix allowed for the research team to ignore those interactions in which design detail was not yet available due to the product design stage.

Ultimately, MIM V3.0 improved the delineation of the boundaries between aspects of manufacturing and their associated definitions, which was successful in eliminating many of the duplicated concerns evidenced in prior case studies.

Lessons Learned

The design for the second generation product continued to evolve during the progression of the assessment. In some cases the assessment, along with the concerns and recommendations were more real-time in nature. Due to the early stage development of this product, many of the MIM interactions involving PMI were not rated as PMI typically will not exist for a product this early in the design phase.

Depending on the stage of the development, the full MIM may not be needed for an assessment of a product in the early design phases. Only certain interactions may be applicable, so a reduced MIM that allows for assessment of known information would be beneficial.

As demonstrated, an analysis can be completed without PMI, but certainly is more thorough if that data is available. In the future, the team may evaluate this shortcoming of the MIM by using terms such as Fit/Form/Function in place of PMI if a prototype of a sort exists.

Conclusions

This paper has provided additional background on the Manufacturability Assessment Knowledge-based Evaluation (MAKE) with focus on the evolution of the taxonomy used to assess product designs. The basis of the taxonomy is the Manufacturability Interaction Matrix (MIM) which provides a structured approach in the manufacturability assessment. Through the use of the MIM, the researchers have devised an approach that is intended to be holistically applied in manufacturability assessments that are inclusive of the entire manufacturing system as opposed to specific focus on the geometry of the parts and assemblies. In the application of the taxonomy to various case studies, lessons learned at each stage are applied to improve the MIM to create a foundation that is both comprehensive and realistic in the time and effort spent performing the assessment. This level of improvement is necessary in order to appeal to the managers and practitioners that may be tasked with manufacturability assessments of their product designs. Future work may involve efforts to add more flexibility to the MIM or evolve the methodology to allow for the application of a manufacturability assessment during conceptual stages of the product development cycle.

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