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# A Model for Advanced Manufacturing Engineering in R&D Technology Projects Through DFMA and MRL Integration

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**Abstract.** The aim of this paper is to present a model that takes into account aspects related to manufacturing engineering in research and development projects. The proposed model integrates the tools of DFMA (Design for Manufacturing and Assembly) and MRL (Manufacturing Readiness Level).Design for Manufacturing and Assembly is used as a method to provide guidance to the design team in simplifying the product structure, to reduce manufacturing and assembly costs, and to quantify improvements. Manufacturing Readiness Level (MRL) is a measure to assess the maturity of manufacturing readiness, similar to how Technology Readiness Levels (TRL) are used for technology readiness. The proposed method was applied in a research and development project at a refrigeration industry, in its technology definition phase. The results were a significant change in product design, bringing benefits as reduction of investment and product cost by 25% and 20%. Is also possible perceive that the anticipation of the manufacturing project, when working simultaneously with the technology maturation is allowing the most reliable debugging at a product, permitting a reduction in the lead time.

**Keywords.** Design for Manufacturing and Assembly (DFMA), Manufacturing Readiness Level , Advance Manufacturing Engineering.

## Introduction

Increasingly, more industry sectors have been affected by the growing and rapid increment of competitiveness, driven by strong level of globalization. Industries are forced to change its way to design and manufacture to deliver the necessary results considering different market situations, whether by government policies or even of each individual company policies. Considering this approach, companies are looking for to integrate Manufacturing Engineering and Research and Development, for example the refrigeration company quoted here, called as industry R. The Manufacturing Engineering working in advanced stage of product development process can help make project in a more efficient way. Efficiency is doing things right and effectiveness is to do right things [1]. The first is related to the operation, which is the optimization of resources means, methods and processes that is how to make the things.

The proposal to increase this efficiency is implement a framework to evaluate the Manufacturing Readiness Levels (MRLs) and Design for Manufacturing and Assembly Methodology (DFMA) through a matrix and apply this matrix on Technology and

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Innovation (T&I) phase. This framework is applied in industry R product development process cycle. MRL is responsible for, defining the current level of manufacturing maturity, identifying maturity shortfalls and associated costs and risks in addition to providing the basis for manufacturing maturation and risk management implementation [16]. The DFMA is used as the basis for concurrent engineering studies to provide guidance to the design team in simplifying the product structure to reduce manufacturing and assembly costs, and to quantify the improvements [2].

## 1. Conceptualization

To introduce MRL is necessary understand current product development process framework for industry R. As shown in Figure 1, the process is structured in phases and decision gates to approval phases. This method is characterized as a system development broken down into a number of sequential sections or stages represented by boxes. The outputs from one stage are used as inputs to the next This framework is the product development process reference model (PDP) that consists of a set of activities through which one seeks, based on market needs along with technological possibilities and constraints, as well as considering the company's competitive and product strategies, to reach a product's design specifications and its production process, so that manufacturing is able to produce it. [4]. In this proposal the MRL should be a tool to support project management decision to in each PDP gate considering the Manufacturing Engineering assessment that is based on index of manufacturability and reliability

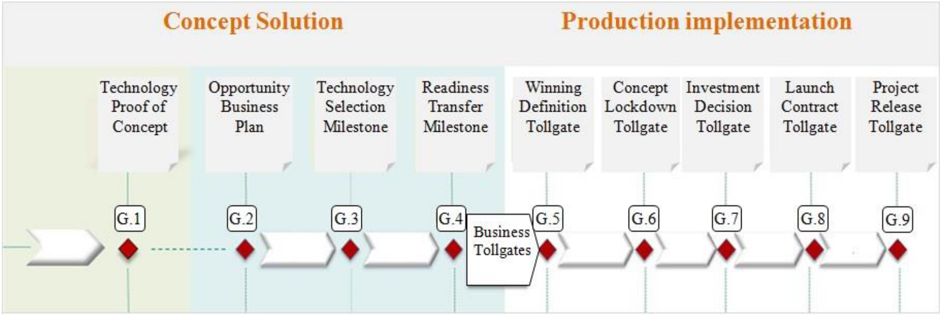


**Figure 1.** Product Process Development framework for industry R.

## 2. Design for Manufacturing and Assembly (DFMA)

The term design for manufacture (DFM) means the design for the ease of manufacture of the collection of parts that form the product after assembly and design for assembly (DFA) means the design of the product for the ease of assembly. Design for manufacture and assembly (DFMA) is a combination of DFA and DFM [2]. There are several DFMA methods or techniques for concurrent engineering development, but the three most well-known are probably the Boothroyd Dewurst DFMA method, the Hitachi Assemblability Evaluation Method and the Lucas DFA Technique [5].

Booth, Lucas and Boothroyd methods have common features and connected topics. Lucas DFA procedure was developed by University of Hull in conjunction with Lucas Engineering. The base of methods is from the same research project as the Boothroyd & Dewhurst DFMA. Thus, these common feature are reduce part numbers and analysis of part geometry for assembly process.

Figure 2 summarizes the steps taken when using DFMA during design, making a parallel about Boothroyd and Lucas methodology. The DFA analysis is first conducted leading to a simplification of the product structure. When DFA began to be taken seriously in the early 1980s and the consequent benefits were appreciated, it became apparent that the greatest improvements arose from simplifying the product by reducing the number of separate parts [2].

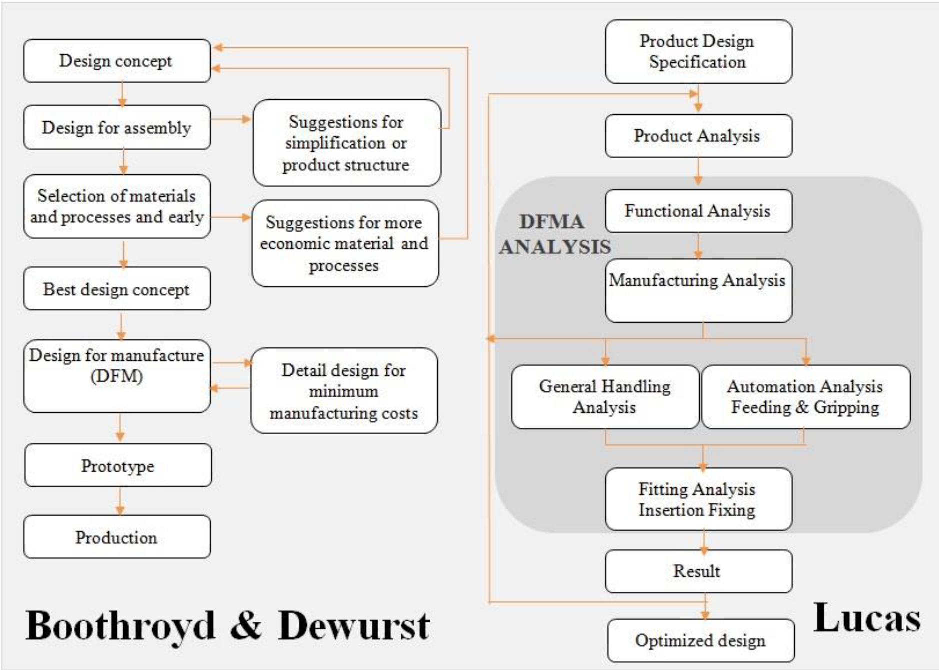


**Figure 2.** Boothroyd and Lucas DFMA application steps [1] [3].

Either Lucas or Boothroyd methods has the first relevant step called functional analysis, both use analogous criteria [2], the objective is the same, reduce part count. The use of Functional Analysis together with DFA able the design team in identifying those parts that are candidates for removal or combination. This involves asking a series of questions to identify which parts of the product are essential or not as well witch parts can be optimized. As a results, the design / manufacturing team has the parts of the product classified in part Type A and Type B. By definition, a type A part is functionally necessary and a type B part should be eliminated or combined where possible [3]. Figure 3 presents a Lucas flowchart, although Boothroyd proposes a similar analysis through 3 questions answers.

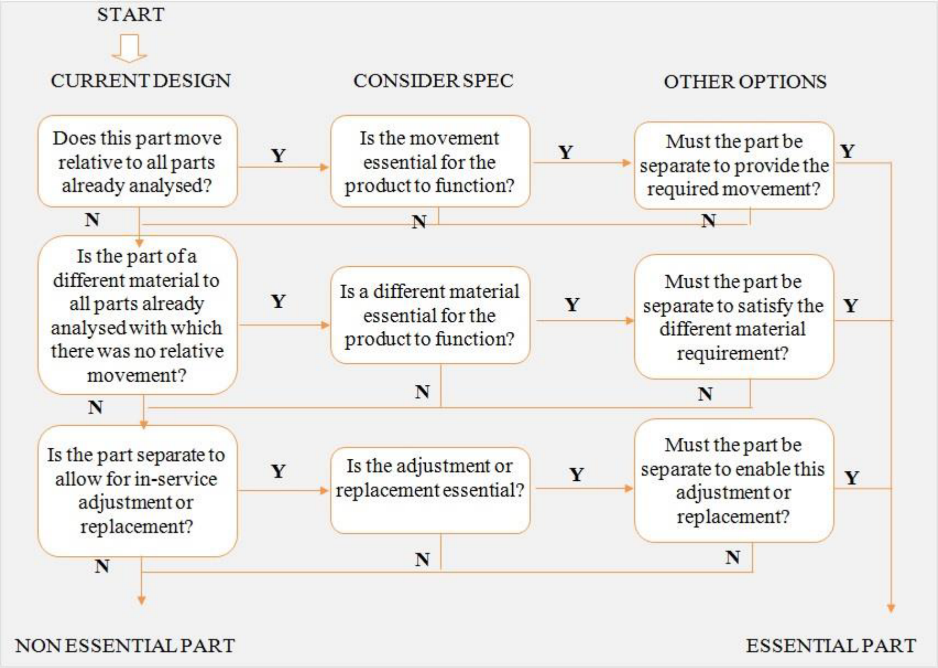


**Figure 3.** Lucas flowchart funtional analysis [ 3].

Following the functional analysis there are two ways to evaluate assembly efficiency, Boothroyd presented in Equation 1 where $N_{min}$ is the theoretical minimum number of parts, $T_a$ is the basic assembly time for one part, and $T_{ma}$ is the estimated time to complete the assembly of the product [1] or Lucas presented in Equation 2 where A is the theoretical minimum number of parts and A+B is the total number of parts [3].

$$AEf = N\min(Ta/Tma) \quad (1)$$

$$AEf = A/(A+B) \quad (2)$$

Both methods have a threshold for design efficiency, Boothroyd follows a tendency based on manual assembly and Lucas suggest design efficiency threshold 60% but a practical working target if often taken as 45% [2].

As a result of experience in applying DFA, it has been possible to develop general design guidelines that attempt to consolidate manufacturing knowledge and present them to the designer in the form of simple rules to be followed when creating a design.

## 3. Manufacturing Readiness Level (MRL)

The definition of MRL is related the conception of technology readiness level (TRL).

Nazanin et al (2009) explain that "Technology Readiness Level (TRL) is a metric that was initially pioneered by the National Aeronautics and Space Administration (NASA) Goddard Space Flight center in the 1980s as a method to assess the readiness and risk of space technology Over time, NASA continued to commonly use TRLs as part of an overall risk assessment process and as means for comparison of maturity between various technologies

In parallel of maturity technology scales measures development was developed the a similar scale to measure the manufacture. The idea was to apply a similar scale addressed in TRL but applied in manufacturing field of knowledge [11].

Manufacturing Readiness Level (MRL) definitions were developed by a joint DoD/industry working group under the sponsorship of the Joint Defense Manufacturing Technology Panel (JDMTP). The intent was to create a measurement scale that would serve the same purpose for manufacturing readiness as Technology Readiness Levels serve for technology readiness – to provide a common metric and vocabulary for assessing and discussing manufacturing maturity, risk and readiness. MRLs were designed with a numbering system to be roughly congruent with comparable levels of TRLs for synergy and ease of understanding and use, (Manufacturing Development Guide, 2010). There are ten MRLs (numbered 1 through 10) that are correlated to the nine TRLs in use. The final level (MRL 10) measures aspects of lean practices and continuous improvement for systems in production.

After the DoD implemented the MRL in 10 steps, there were derivations, the first concerns about the Rolls-Royce, responsible for development of turbines for aircraft, which created a scale of 9 steps based on the scale proposed by DoD, call Manufacturing Capability Maturity Level (MCRL) where each of the nine steps of TRL is connected directly with MCRL, and is applied to the entire "supply chain"[11] (Figure 4). In addition to the Rolls-Royce range, two other scales aimed to determine the level of maturity of manufacturing processes were created, the first was (IMRL) created by the nanotechnology industry due to the high differential appeal of innovation, which is also based on the TRL model, and the second used by the Department of Aviation General Electric in 2010 which confirms that the use of TRLs and MRLs are the right way to act systematically to reduce risks and create a common language throughout the industrial base. MRL specifically gives its return to the company by adding value to process capability and maturity of the production plan.

Each one of these 10 MRLs has a specific objective that goes from basic manufacturing issues up to full rate production and best practices, following Manufacturing Readiness Level (MRL) Desk book (2011) definitions.

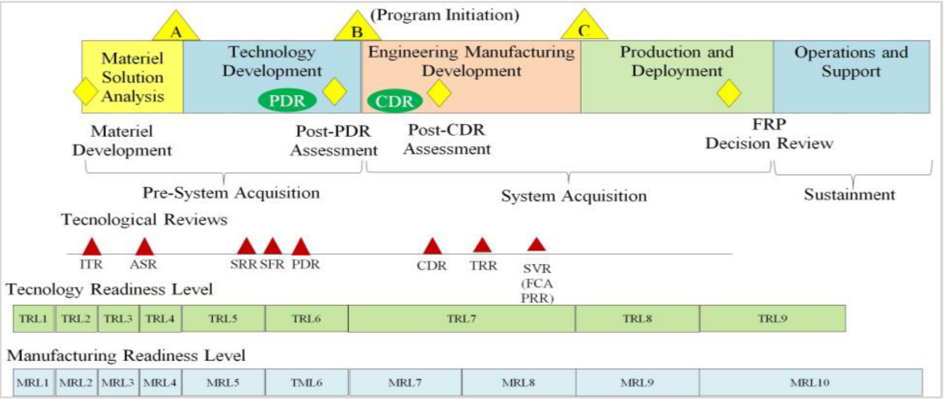


**Figure 4.** DoD Acquisition life cycle.

## 4. Proposed model

The process supported to measure in the project the manufacturing maturity level associated with DFMA rules is presented on Figure 5. The scheme of the process includes inputs, tools & techniques and outputs. The input is the product design proposal and the output is the maturity evolution indexes. And, to support this process was developed a DFA and DFM evalution sheet and DFMA&MRL matrix.

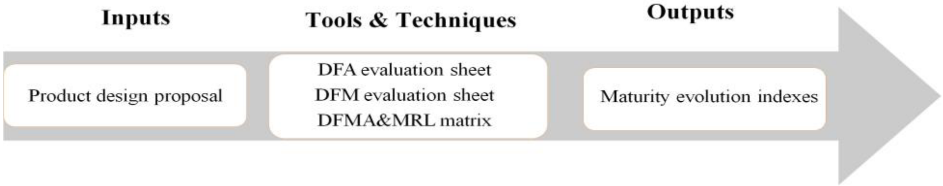


**Figure 5.** Manufacturing maturity evaluation process.

DFA evaluation sheet is an adaptation of DFA evaluation spreadsheet from Stienstra (2016) and Sohan (2015) including Lucas Methodology sub-factors and penalty scores to be possible make the math used to calculate final scores. Lucas methodology was selected for this evaluation due to be possible proceed with analysis without numeric evaluations about cycle time, which is strictly necessary at the beginning phases of the project where there are only concepts of product. The spreadsheet is divided in 8 levels, identified as L1 to L8 in Figure 6, level 5 (L5) is the most important because it is the part that the project team will fill in, comparing product component design according factors presented on level 2. Item 5.1 must be filled in with Bill of Material from a design under evaluation, 5.2 must be filled in with the number of components related to the Bill of Material (BOM) and field 5.3 must be used Yes or No, Low, Medium or High according to the answer drivers on level 3 as for example in Figure 6. Level 1 (L1) has the main factors that the project's design will be analyzed, level 2 (L2) are sub-factors deployed from (L1) that permit a more accretive analysis about each item. Level 3 (L3) presents the answer drivers to be inserted on field 5.3 during project analysis, level 4 (L4) has the penalty factors that will be used to calculate total penalty scores for handling and fitting. As soon as the project team has finished to fill in level 5 the results will be presented on levels 6, 7 and 8, where level 6 (L6) is the total score created to be possible differentiate different component designs. This score correlates levels 4 and 5, and the calculation method is presented in Equations 3 and 4. Equation 3 is applied for DFA complexity, Functional Analysis & Redesign Opportunities and Full Proof, while Equation 4 is used for Handling and Fitting using penalty factors ( PFmax and PFmin) from level 4 DFA evaluation sheet, Figure 6.

$$Total = \sum YES \tag{3}$$

$$Total = \sum NO \times PFMax + \sum YES \times PFMin \tag{4}$$

Level 7 (L7) aims to relativize rough numbers from equations 3 and 4 to be possible make a comparison among designs and projects. From (a) to (f) Equation 5 is applied and the best score is 100%. From (g) to (u) Equation 6 is applied, this value aims present penalty factors, so the best score is 0. To finalize spreadsheet level 8 (L8) there is the DFA global index, a metric used to be possible compare different designs and projects in a higher level along its life cycle, and are grouped by common objectives : DFA Index (AA), Cost Drive Index (BB), Full Proof Index (CC), Handling Index (DD), Fitting Index (EE), , and Other Operations Index (FF).

$$DFApartial\,index = \frac{\sum YES}{\sum YES + \sum NO} \times 100\% \tag{5}$$

$$DFApartial\,index = \frac{Totals}{b} \tag{6}$$

| L1 | Component of Subsystem identification | DFA complexity | Functional analysis & Redesign opportunities | | | Full proof | | Handling | | | | | | | Fitting | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L2 | Insert a Drawing View of component of Subsystem | Number of parts (Np) | Theoretical minimum part | Standard Part | Relative Cost | Wrong part | Wrong way | Tangle,Nest,Sticky | Flexible | Fragile | Sharp,Abrasive | Slippery | Rotation, Oientation | Plier , 2 hands | Align,Locate | Holding down | Insertion | Obstructed access | Self-holding | Screw,drill,bend, rivet,twist, crimp | Snaps | Weld or adhesive |
| L3 | Answer driver | N.A | Y/N | Y/N | L/M/H | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N | Y/N |
| L4 | Penalty factor Minimum (PFMin) | N.A | N.A | N.A | N.A | N.A | N.A | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 1,0 | 0,0 | 0,0 | 0,0 | 0,0 | 1,0 | 0,0 | 0,0 | 0,0 |
| | Penalty factor maximum (PFMax) | N.A | N.A | N.A | N.A | N.A | N.A | 2,0 | 0,6 | 0,4 | 0,3 | 0,2 | 0,4 | 1,5 | 0,7 | 2,0 | 0,6 | 1,5 | 2,0 | 4,0 | 0,7 | 4,0 |
| L5 | **1 SB 1** | | | | | | | | | | | | | | | | | | | | | |
| | 1.1 Comp.A | x | Y | Y | L | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| | 1.2 Comp.B | y | Y | Y | L | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| | 1.n Comp.N | z | N | N | H | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| | **n SB n** 5.1 | 5.2 | | | | | | | | | 5.3 | | | | | | | | | | | |
| | n.1 Comp.A | w | Y | Y | M | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| | n.2 Comp.B | k | Y | Y | M | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| | n.n Comp.N | j | Y | Y | L | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| L6 | **Totals** | **a** | **b** | **c** | **d** | **e** | **f** | **g** | **h** | **i** | **j** | **k** | **l** | **m** | **n** | **o** | **p** | **q** | **r** | **s** | **t** | **u** |
| L7 | **DFA partial Index** | **A** | | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** | **O** | **P** | **Q** | **R** | **S** | **T** |
| L8 | **DFA global index** | **AA** | | **BB** | | **CC** | | **DD** | | | | | | | **EE** | | | | | | | **FF** |

**Figure 6.** DFA evaluation sheet.

To complete DFMA analysis a DFM evaluation sheet is used, Figure 7 that gives 3 DFM partial index, manufacturing relative costs (Rc), manufacturing processing cost (Pc) and manufacturing material costs (Mc), which will be grouped to form a DFM Global Index called Manufacturing Cost Index, following the logic of DFA Partial and Global Indexes. It must be used with the same BOM list used on the DFA evaluation sheet. This spreadsheet follows the method proposed by the Lucas Methodology [7].

| Volume | Shape Complexity | Qty | **Rc** | Cc | Cmp | Cs (Ct or Cf) | **Pc** | **Mc** | V | Cmt | Wc | **Mi** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subsystem total** | | | | | | | | | | | | |
| **SB 1** | | | | | | | | | | | | |
| Comp.A | | | | | | | | | | | | |
| Comp.N | | | | | | | | | | | | |
| **SB n** | | | | | | | | | | | | |
| Comp.A | | | | | | | | | | | | |
| Comp.N | | | | | | | | | | | | |

**Figure 7.** DFM evaluation sheet .

To know in what step of maturity (MRL) is the project, was done one adaptation on the MRL steps of the "DoD acquisition life, Figure 3, for the current PPD Industry R reference model, Figure 1. For the first step, although the product is different, a direct correlation was identified between the two cycles, DoD Pre System Acquisition and Industry R PDP up to CLT gate, and these correlations and MRL adaptation are presented in Figure 8.

To integrate MRL, DFA and DFM evaluation sheet was created a matrix called DFMA and MRL integrated matrix, Figure 10, where section A presents the the results of each maturity step under evaluation from MRL2 to MRL4 and a recommended threshold value to drive project decisions and risk assumptions. Section B is a space to insert a brief description about product changes from maturity steps evolution and C is a deployment of A to became easier for project management and project team identify the relevant points that must be planned for the next phase. To validate the model is done a Case Study applied at a real project at Industry R for MRL2 to MRL4 and measured the evolution.

| DoD Acquisition Life Cycle | Pre systems acquisition | | | | | |
|---|---|---|---|---|---|---|
| | Materiel Solution Analysis | | | | Technology Development | |
| DoD MRL | MRL 1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 |
| Enterprise R PPD | TCP | OBP | TSM | RXM | WDT | CLT |
| Enterprise R MRL Adaptation | MRL1 | MRL 2 | MRL 3 | MRL 4 | MRL 5 | MRL 6 |
| | Basic Manufacturing Implications Identified [Shortfalls and Basic Research] | Manufacturing Concepts Identified[Applied research in solutions] | Manufacturing Proof of Concept Developed [Analytical laboratory experiments] | Capability to produce the technology in a laboratory environment [Technology Ready] | Capability to produce prototype components in a production relevant environment [Acess industrial base] | Capability to produce a prototype system or subsystem in a production relevant environment [Ready to start acquisiton program] |

**Figure 8.** MRL adaptation for PPD at Industry R.

## 5. Model Application

The model was applied following the sequence presented in Figure 9, each box follows the rules previously oriented for Boothroyd and Lucas methodologies. The project team is responsible to fill in level 5 (L5) on the spreadsheet, Figure 6, on items 5.1 and 5.2 inserting data from the BOM list and number of components and item 5.3 filling in each blank space with an answer driver from level 2 related to each sub factor at level 2. For DFM evaluation sheet it's necessary to fill in the DFM sheet based on Lucas Methodology orientations.

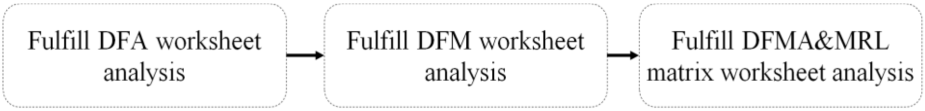


**Figure 9.** Methodology sequence application.

## 6. Results

The model was applied in a project along of 3 phases of maturity, MRL2 to MRL4, by Process Manufacturing Engineering to support and drive product modifications. The results, as presented in Figure 10, were a modification in all concept design. With the increase in the DFA index, it was possible to reduce assembly risks with not known or complex technologies required to product previous design beyond of a reduction of transformation cost due head count reduction. Handling and Fitting were improved due product concept changes and will allow another step of improvement on the next phase. The investments on manufacturing process were reduced in 25% this results were driven by the manufacturing process cost index that presented an improvement of 49%, and the main impact was the change of precision machining operations for the stamping process. The design change also provided a product design cost reduction of around 20% due not be more necessary use of expensive materials or assuring tight tolerances for components. Another benefit was reducing project lead time due process engineering team work in advanced steps avoiding future looping during acquisition phase.

| Better | ↑ | ↑ | ↓ | ↓ | ↑ | ↓ | ↓ |
|---|---|---|---|---|---|---|---|
| **Level Evaluation** | MRL 4 | | | | | | |
| **MRL 4** | 70% | 45% | 2,21 | 3,99 | 79% | 92 | 1,14 |
| **MRL 3** | 61% | 42% | 2,21 | 4,14 | 76% | 103 | 1,14 |
| **MRL 2** | 53% | 35% | 2,40 | 5,20 | 67% | 212 | 1,50 |
| **Threshold Recommendation** | >=60% | *Bt2 | <=2,5 | <=2,5 | *Bt2 | *Bt2 | *Bt2 |
| **Product Change Point / Level of changes** All concept design was modified from MRL2 to MRL3 and a design optimization was done on MRL4 | **DFA Index ↑** | **Cost drive ↑** | **Handling Index ↑** | **Fitting Index ↑** | **Full Proof Index ↑** | **Manufacturing process cost index ↑** | **Other Operations Index ↑** |
| Is it a **standard part**? | | **21%** | | | | | |
| Component cost with **lower impact** | | **68%** | | | | | |
| Meets the **Handling** rules: Not Tangle,Not Nest, Not Sticky | | | **0,7** | | | | |
| Meets the **Handling** rule: Not flexible | | | **0,1** | | | | |
| Meets the **Handling** rule: Not fragile | | | **0,0** | | | | |
| Meets the **Handling** rule: Not sharp/Abrasive | | | **0,0** | | | | |
| Meets the **Handling** rules: Not slippery | | | **0,0** | | | | |
| Meets the **Orientation** rule: It´s not hard to see rotational orientation | | | **0,0** | | | | |
| Meets the **Size** rules: Not Necessary use Plier , Tweezers or 2 hands | | | **1,4** | | | | |
| Meets the **Alignment** rule : Not difficulto to align,locate? | | | | **0,4** | | | |
| Meets the **Process Direction** rule Holding down requirements? | | | | **0,3** | | | |
| Meets the **Insertion Force** rule: Is it smotth to insert?(There´s no resistance) | | | | **0,1** | | | |
| Meets the **Acess/Vision** rule:Has no obstructed access ?( good visibility ) | | | | **0,3** | | | |
| Meets the **Part Placing** rule: The part can be self-holding assembled? | | | | **1,7** | | | |
| Meets the **Fastening A** rule: Can it be assembled without screw,drill,bend, rivet,twist or crin | | | | **1,1** | | | |
| Meets **Fastening B** the rule: Can it be assembly without snaps ? | | | | **0,1** | | | |
| Meets the rule: Is NOT possible assembly **wrong part** | | | | | **100%** | | |
| Meets the rule: Is NOT possible assembly **wrong way** | | | | | **53%** | | |
| Manufacturing **Relative Costs** ( Rc) | | | | | | **44** | |
| Manufacturing **Processing Costs** (Pc) | | | | | | **16** | |
| Manufacturing **Material Costs** (Mc) | | | | | | **24** | |
| Meets the rule:Is possible assemble **without** using weld or adhesive? | | | | | | | **1,14** |

**Bt2 :( Better than previous maturity level ), there is no scientific threshold for this index but must be better than previous maturity level.*

**Figure 10.** DFMA and MRL Integrated Matrix.

## 7. Conclusion

This model is a important tool to permit manufacturing process engineering work in a concurrent engineering environment mainly during the preliminary steps of research, due to the high influence on product design that will result in lower transformation and material costs, lower investments as well as shorter lead times, at the same time making it possible to follow the project maturity evolution considering aspects related to Process Manufacturing Engineering therefore avoiding and mitigating future risks that normally appear in the acquisition phase.

The limitation of this study is for preliminary steps of a project during concept definition and preliminary prototypes, future works can use other MRL levels and establish DFMA connections.

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