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Abstract- Many companies have already been replacing components of their products with materials offering low-cost, weight-reduction options and also to supplement their green footprint on environment. This paper gives a systems approach to the whole metal to plastic replacement process that is common today in fields like automotive, medical, electrical electronics among others. This work clearly shows how a metal to plastic conversion project, right from the concept to the production stage, can be seen as a system with discrete inputs influencing the process due to their interdependency and how it leads to the desired output based on specific requirements. This paper would assist any project taken up in an industry or as a research study, aiming to replace a metal with a plastic component successfully.

Keywords*- systems approach; plasticmoulding; metal to plastic replacement; metal to plastic conversion; simulation; analysis.*

I. INTRODUCTION

Plastic engineering is synonymous in almost all modern day industries due to versatility of plastic materials today. Right from transplants in the medical field to the soles in footwear industry, there is a plastic available to suit every possible requirement. All of these have been possible only due to the relentless research and development in the polymer science / plastic engineering field. Add to this, the blurring of lines between various engineering fields and we have a whole new dimension. Today we can say that plastic engineering is a mix of mechanical engineering and chemical/polymer engineering with various other facets of science and technology.

In the persistent search for cost reduction, plastics continue to advance in replacing metal parts. Performance benefits like weight reduction and corrosion resistance can be achieved other than lowering cost. However, plastics materials which are fundamentally different from metal in molecular structure are vitally different from metals not only in intrinsic short term properties but also in the way they react under application to the influences of time, temperature, and load. Failure to use techniques that consider the influence of these variables in the application of the part frequently leads to products that are either over- or under- engineered.

Today we can see metal to plastic replacements in industries like automotive, aviation, medical, lighting / electrical, electronics, furniture and so on. Automotive industry has now shifted majorly from metals to plastics for many of their components, presently made in iron or aluminium alloys, which provide them with weight reduction opportunities, thereby leading to cost savings, energy savings and improving their carbon footprint. Metal to Plastic Conversion is now seen in automotive body parts, power-train, motor management, brake parts, fuel pump parts, etc. In the aviation industry, Plastic composites make up 25% of the total airframe on the Airbus A380, where composites replace aluminum [1]. In food processing industry, stainless steel food hoppers, used for the accurate dispensing of ‘sticky’ foodstuffs, have been substituted with metal filled acetal polymer thereby significantly improving the feeding of high-adhesion foodstuffs [2]. Examples of successful metal to plastic replacements are not limited to the ones above.

A. Benefits of Metal to Plastic Replacements

Typically some of the main merits of plastics over metals are [3]:

1) Weight reduction since all plastic materials including composites are lighter than metals like steel and aluminium.

2) Fewer assembly operations may be achieved.

3) Reduced secondary finishing.

4) Reduction in total system costs.

5) Electrically non conductive, predominantly.

6) Ability to withstand temperatures to more than 500^{o}F and most chemicals and corrosive environments.

7) Greater design freedom, e.g. part complexity may be worked upon depending upon requirement.

8) Opportunity for parts consolidation.

9) Broad range of properties tailored to meet specific applications.

10) Energy efficient since plastic part production is less energy consuming compared to metal part production or metal forming like die casting, sand casting, etc.

B. Need for a Systems Approach

Industries going for metal to plastic conversion today use many tools for this purpose. A fair amount of experience has been gained in this field with tried and tested methods developed by companies specialised in this area with the help of plastic raw material suppliers like DuPont, DSM, Sabic, Ticona, etc. However, metal to plastic replacement projects still have hurdles because of the continuing entry of new products and applications yet untried. This sometimes leads to no proper direction to problem-solving, data insufficiency and lack of clarity on relationship between important parameters of new product which may ultimately lead to project failure. Hence a necessity is created to bring in a systems approach. By viewing metal to plastic replacement project as a system, we can actually compute the various inputs that are required for the process and successfully achieve the output of substituting a metal component with a plastic one.

II. THE SYSTEMS THINKING

A. Understanding a System and the Systems Approach

A system is an assemblage of interrelated parts that work together by way of some driving process. These component parts, or elements of the system are intimately linked with one another, either directly or indirectly, and any change in one or more elements may affect the overall performance of the system, either beneficially or adversely.

C. West Churchman provides an excellent discussion of the systems approach in his text [4]. Churchman begins by defining systems as, “sets of components that work together for the overall objective of the whole.” A systems approach is strongly associated with systems thinking, i.e. by viewing "problems" as parts of an overall system, rather thanreacting to specific part, outcomes or events and potentially contributing to further development of unintended consequences.

As per the suggestion of Russell Ackoff, a system is a set of two or more interrelated elements with the following properties:

1. Each element has an effect on the functioning of the whole.
2. Each element is affected by at least one other element in the system.
3. All possible subgroups of elements also have the first two properties [5].

Thus, applying systems approach to metal to plastic replacement is all about seeing every factor affecting the project as a part of the whole. Every parameter is interlinked, be it relation between design modification and strength of the part, relation between plastic processing parameter and warpage of the part or that between choosing right material for mould and mould life and so on. The classification of systems into hard and soft represents an effort to draw attention bothto the degree of knowledge about a system, and about the system's aims or purposes. P. Checkland developed this classification to represent two ends of a continuum [6]. The metal to plastic replacement project can be considered as a hard system. This is simple because, hard systems are easier to define and have more clear-cut aims or purposes. They are typically the subject matter of engineers concerned with real-world problem-solving. Simplicity of purpose and clarity of boundary, however, do not necessarily mean ease of design, evaluation and manufacture. Hard systems can indeed be highly complex [7].

B. A Systems “Model” for Metal to Plastic Replacement

Fig. 1 shows a typical model of a system for metal to plastic replacement. This is a general model that could be used for any product. The boundary for this system will be the product’s application requirements and working conditions.

1) Inputs to the system: For any project to materialise successfully, the input plays an important role. In case of a Metal to Plastic Project, where the technical data for different plastic materials alongwith the actual working conditions of the part help us to choose a specific plastic material that will suit the requirement. Availability of machines is another important input because this project involves machines for plastic processing, machining or mould / die components, testing, etc. Similar to plastic materials, technical data of raw materials for mould / die components (steel, phosphor bronze, etc.) should also be available to choose between different grades for different mould / die components. People with technical knowledge, skill, experience & expertise in the fields of plastic engineering, viz. plastic product design, mould design and plastic processing form a crucial part of the project team. Computer Aided Design / Engineering / Manufacturing (CAD/CAE/CAM) softwares like SolidWorks, ProE / Creo, Unigraphics NX etc. have to be available for various design, simulation and manufacturing requirement. Last but not the least, tools and data should be available to understand the feasibility of the metal to plastic replacement project based on cost and energy effectiveness.

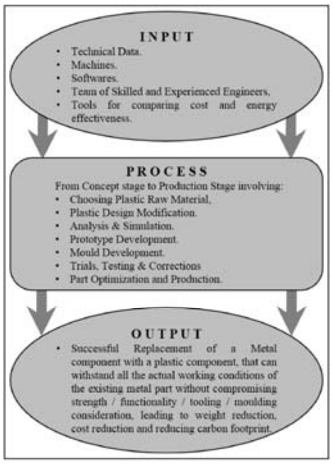

Figure 1. **A Systems “Model” for Metal to Plastic Replacement.**

2) The actual process: Plastic material selection is the most essential step which will make or break the whole project since the plastic has to withstand the existing metal part's conditions. After studying the existing metal design, possible modifications to the existing metal design will have to be applied using plastic product design principles.

Once the design is ready, analysis & simulations can be performed. Finite Element Analysis (FEA) helps in understanding how the part will behave with respect to the working conditions. Mould Flow simulations helps in understanding the approximate measure of the part under moulding conditions. A prototype can be created internally or externally by the company with the final design of the part and the plastic product can be evaluated for all basic criteria.

After understanding the proper tooling considerations, the mould designing can be done and the mould manufactured. The trials of the parts can be taken, which after testing / inspection leads to mould correction, if necessary. Finally the part can be optimized and the actual plastic part production can be started.

3) The output: Finally, the objective of the project equals as the output, i.e. to successfully replace a metal component with a plastic component, that can withstand all the actual working conditions of the existing metal part, i.e. temperature, pressure, corrosive environment, loading, etc.without compromising strength / functionality / tooling / moulding consideration, leading to weight reduction and cost reduction. Ultimately, since energy consumed per plastic part production is lesser than that of metal part, we can positively achieve lesser carbon footprint.

III. SYSTEMS APPROACH TO METAL TO PLASTIC REPLACEMENT

Based on the generalized systems "Model" for metal to plastic replacements, we can now easily associate every element of this system with its function and its interdependency on other elements, in detail. Thus, a systems approach is now developed for metal to plastic replacement projects as shown in Fig. 2.

A. Understand the basis & structure of systems approach:

Before the systems approach is dealt with in detail, it is of utmost importance to understand that the elements of this system are interlinked. Some interrelationships may be cyclic, while others may be one-way only. These elements may themselves be capable of further breakdown into other smaller components, and may thus be regarded as sub-systems of the overall system. These sub-systems are not mentioned in Fig. 2 since it would be too exhaustive. However, care is taken that examples of these sub-systemsare explained in the forthcoming units along with their related elements.

B. Begin with the Concept Stage:

For replacing metals with plastics, a strong team's expertise can make the process more efficient bycompressing the design cycle, reducing costs, and improving quality. Depending on the product, it can include representatives from production, design, engineering, research and development, sales, marketing, purchasing, and quality control, when required. The internal team manages all activities and defines design and performance requirements. Each player has a specific role to contribute to the system.

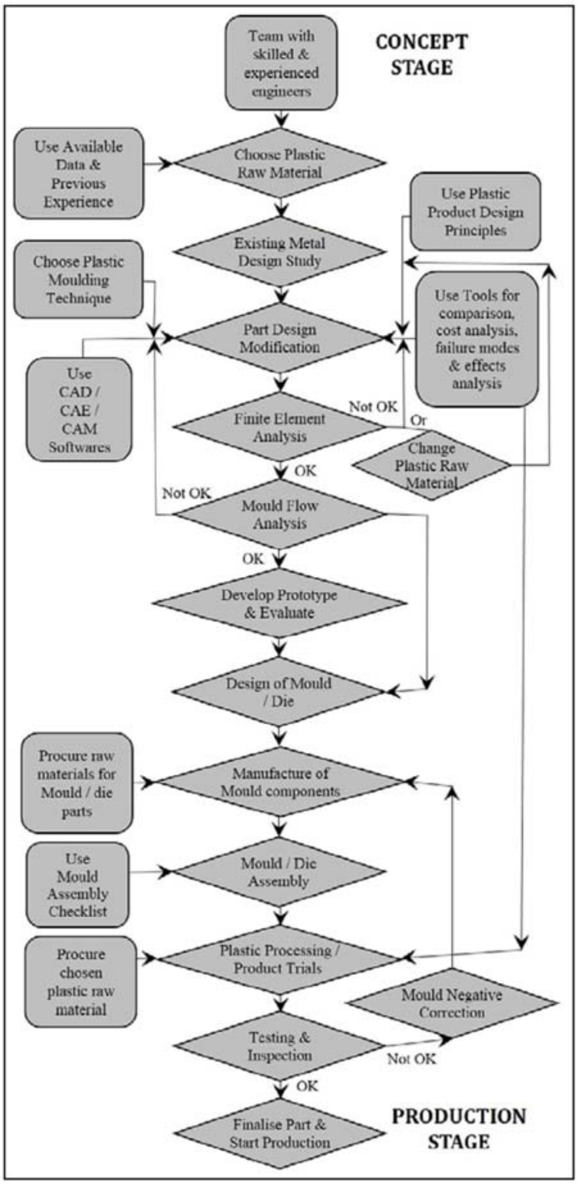

Figure 2. **Generalised Systems Approach to Metal to Plastic Replacement.**

The team needs to clearly define and understand the application requirements for the product by identifying the basic weaknesses of the incumbent conversion technology and material, building a strong value proposition as it pertains to the application and selecting the right material. The external team acts as a sub-system here contributing to the overall system along with the internal team. The external team contains those who understand the entire process, such as a plastic supplier who can provide data on plastic properties and performance and can assist in preliminary or detailed design, prototype testing, fabrication, and pre-production evaluations.

The external team may also contain mould and tool builders (if mould / tool is not built in-house), experts from customers, industrial design firms and assembly equipment supplier. It is also prudent to select the plastic moulding technique that will be best suited for manufacturing the part. Most commonly used is the injection moulding technique.

The most successful metal replacement efforts generally employ a design team that combines concurrent design methods with careful development and testing. Some companies take a less effective, but all too common approach. If they appoint an individual as the plastics expert, choose a part for conversion, and assign unrealistic time lines, then little teamwork is involved and failure is almost ensured.

C. Choose the Plastic Raw Material correctly

This forms the most important element in the system. In choosing the right plastic, it is significant to maximize system performance at the lowest possible cost. Material selection is particularly difficult because plastics offer literally thousands of options. The working conditions of the product need to be first understood. Plastic selection criteria must include, not limited, to the following:

- Heat resistance – covering upper & lower peak temperatures.
- Ability to withstand mechanical loadings and resist creep / fatigue.
- Stiffness and strength.
- Chemical resistance, that may cause cracking, crazing, discoloring, and softening.
- Melting - whether during handling, assembly, finishing, or use.
- Aesthetics to be achieved after moulding.
- Availability of the plastic raw material.
- Compliance to laws and regulations.

The characteristics of the plastic material also affect part and mold design. Key plastic qualities to consider include:

1) Flowability - which depends on melt viscosity, shear resistivity and thermal conductivity, is affected by flow length in the cavity; gate type, size, and placement; and mold cavity cooling.

2) Heat transfer coefficient - Proper heat transfer prevents warpage due to differential cooling. It also maintains a uniform temperature in the mold so optimum plastic characteristics develop by either crystallization of crystalline plastics or annealing of amorphous ones.

3) Plastic shrinkage is important because mold cavities are sized so that, upon cooling, part dimensions fall within the design tolerances. The filler type and orientation affect shrinkage.

D. Study, Design & Simulation/Analysis of the part

The design of the part should be from the perspective of the following points:

1) The Reducing number of parts-
   a. Parts consolidation.
   b. Fastener reduction.

2) Improve assembly efficiencies-
   a. Reduce the need for secondary operations.
   b. Simplify assembly methods – snap fits, press-fits, heat staking.
   c. Eliminate sanding, grinding, painting.

3) Optimize part handling-
   a. Consider designs that limit assembly orientation options.
   b. Minimize added handling difficulties.

Before the design modification is undertaken, a detailed study of the 2D drawings of the existing part is essential to understand the tolerance specifications that are given for the metal part and analyse if these are acceptable & achievable with a plastic part. Further, the 3D models of the existing parts have to be remodelled and tweaked as per the Plastic Product Design Principles to take into consideration the part complexity, part strength & functionality and tooling complexity. Depending upon the number of plastic components or the assembly requirements, the possible assembly methods will have to be worked out.

As mentioned earlier, in the system of metal to plastic replacement, the element of part design and the elements of simulation / analysis have a cyclic link, since any change to the former affects the latter and vice-versa.

CAD software will have to be used for possible modifications to the existing metal design like reducing thick sections, removing complex features, providing tooling draft, giving additional ribs for strength, etc. Tooling considerations have to be deliberated during the plastic product design, so that elimination of any undercut features or complex mechanisms can be achieved to the maximum extent possible. In certain metal parts, self tapped threads are provided for mounting of bolts, which cannot be given in a plastic part since plastic threads would give way due to excessive torque and stress relaxations.

Instead metal (brass or steel) inserts may be provided in the plastic design to take the load and torque of bolts [8]. Knurling are provided to metal inserts to ensure that the roughness created by it will help in fixing the insert to the plastic surface and prevent movement. If no knurling is used, the plain outside surface of the metal insert will tend to rotate after plastic moulding during tightening of bolt and also exhibits s a very low pull-out load.

CAE - Structural FEA is especially useful in evaluating stress and deflection in complex parts. It is an analytical prototyping process that starts with simple linear models and may proceed to more complex ones. As a staged process, it repeatedly refines and re-analyzes the part until confidence in its performance is attained.Thus FEA helps in re-tweaking the design and arriving at the best possible design. Sometimes it may even lead to changing the plastic raw material.

Mould Flow analysis (MFA) evaluates gate position and size to optimize plastic flow. It also defines the location of weld lines, areas of excessive stress on the melt, effects of wall and rib thickness on flow, cooling analysis for mould temperature distribution and cycle time; shrink analysis for dimensional control; moulded-in stresses, and warpage predictions. Thus MFA reduces the time and cost to develop mould tools. Other finite-element design tools for molds include: cooling analysis for mold temperature distribution and cycle time; shrink analysis for dimensional control; molded-in stresses, and warpage predictions.

E. Develop Prototype and Evaluate

Prototypes highlight design and assembly problems, and allow testing of essential properties. The more accurate the prototype, the more expensive it will be. In general, accurate prototypes are needed for complex parts having tight tolerances and great detail. Prototyping can be done by using desktop manufacturing techniques, such as simple 3-D milling machines, selective laser, sintering, and stereolithography (SLA).

Prototype testing leads to design refinements, final material selection, and the specification of production details. Dimensional stability, strength, and rigidity, combine the effects of several factors and are difficult to measure in the lab. For example, dimensional stability might combine coefficient of thermal expansion, moisture absorption, post-mold shrinkage, and relaxation of molded-in stresses. Assessment of how a plastic performs in such areas often depends on prototype testing.

In testing prototypes, it is recommended to use the original design criteria. Most evaluations of exact prototypes have three areas of concern: mouldability, part performance, and assembly. Problems that arise during prototype evaluation can often be corrected by looking at the entire system.

Although many solutions can be found by studying the design, plastic, and process for aspecific part, the best solution may involve other areas of the system. For example, it may be less expensive to alter a metal part that is joined to a plastic part by changing a control program on a numerically controlled milling machine than by making modifications to the injection mould for the plastic part.

The prototype tool is often used as the pilot production tool. The production tooling should have the same cavity dimensions and plastic flow as the prototype tool. If the production tool differs from the prototype tool, consider the new tool as another prototype and retest the initial parts made from it.

F. Design, Manufacture& Assembly of Tool / Mould

MFA gives a lot of critical input for mould design as seen in the earlier unit. Often a mould concept is developed and a meeting is schedules between the engineering, design and the production teams to streamline the design and arrive at the best possible concept. Mould / die is designed in the CAD software and checked for completeness. When mould is to be made in-house, the mould drawings and models may be released for manufacturing of individual mould components.

Mould/Tool design is determined largely by the fabrication process. In injection molding, the designer must deal with placement, type and size of gates, size and number of cavities, draft, the runner system, and slides. Parts with holes or depressions perpendicular to the direction the mold opens and closes must have side-action slides/cores.

This is expensive and requires more maintenance than a simpler tool. In extrusion technique the designer must deal with die & adapter assembly, spider and mandrel design. Design of the tool will depend from one moulding process to another.

Commonly used machines today for this purpose are the Computer Numerical Controlled (CNC) milling machines, Wire Electrical discharge Machining (EDM) machines, Spark EDM machines among others. With the help of CAM software, machining of mould components can be programmed.

Common smaller mould components like ejector pins, shot counters, etc. may be ordered externally. It is always advised to use a checklist during mould assembly to eliminate problems like cooling water or oil leakage during production or damage to internal side cores.

G. Plastic Moulding / Mould Trials

As we know that Injection moulding is the most common technique used in metal to plastic replacement projects, this technique in itself is a system having many interdependent processing elements / parameters. Trials are often performed before full production runs in an effort to predict defects and determine the appropriate specifications to use in the injection process.

When filling a new or unfamiliar mold for the first time, where shot size for that mold not known, a technician/tool setter may perform a trial run before a full production run. He starts with a small shot weight and fills gradually until the mold is 95 to 99% full. Once this is achieved, a small amount of holding pressure will be applied and holding time increased until gate freeze off (solidification time) has occurred.

A well-designed injection mould allows for the broadest possible processing window so that plastic and process variables can shift somewhat over time without loss of part quality. In the short term, for example, this allows for changes in plastic viscosity and for process variations in hydraulic pressure or barrel temperatures. It also allows for long-term variations, such as screw and barrel wear that affect melt quality.

Mould trials give us the parts that may have scope for improvement or help us in identifying the parameter in the machine or the system which can be tweaked for achieving better parts.

H. Testing / Inspection, Corrections and Final Production Stage:

The parts produced in the trials undergo inspections including visual, to observe any defects such as sink marks, burn marks, flow marks, etc. which may be controlled by modifying process parameters. As per the specifications or customer requirements for the final part produced, tests are conducted, such as torque test for inserts; centre distances for mounting holes, etc. to find out whether the part is within specified tolerances.

These tests may include dimensional, form and fit, stress/strain, aesthetic and colour checks. Dimensional checks may incorporate Go/No-Go gauges or the part may be put in measuring fixtures and measurements may be made for critical dimensions. The gauges and calipers should always be calibrated before measurements. Operators must be trained to do these tests as the results will be used to verify the quality of moulding and parts. Measurements should always be taken after a predetermined cooling period to avoid shrinkage errors and to have uniformity of measurement data.

Negative corrections on the mould may be required to nullify warpage or flatness characteristics on the part. Corrections may be done on the same mould component or another mould component may be manufactured to accommodate the changes. This gives another example of the influence of one element over the other in the system of metal to plastic replacement.

Once the part is optimized, production capability is established, and purchase order is released, production of the part can be started.

IV. TOOLS FOR COMPARISON, ANALYSIS & QUALITY CONTROL

Throughout the metal to plastic replacement project, various analysis with respect to cost, design, production and quality will have to be performed. These tools help in reinforcing the project goals and choosing the right part when a problem is encountered. Though there are numerous tools available today, only a few critical ones used widely by companies today are covered here.

Cost-benefit Analysis (CBA) or Benefit Cost Analysis (BCA) may be performed before the start of the project to understand economic feasibility. BCA is a systematic process for calculating and comparing benefits and costs of a project. Cost-effectiveness analysis (CEA) is a form of economic analysis that compares the relative costs and outcomes (effects) of two or more courses of action. Also, Total Cost of Ownership (TCO) is a financial benefit analysis used to gauge the viability of any capital investment. A company may use it as a product/process comparison tool. Technical feasibility study may be performed to eliminate ambiguity in later stages of the engineering project.

Process may be improved by incorporating Six Sigma techniques, which is a fact-based, data-driven philosophy of quality improvement that values defect prevention over defect detection. It drives customer satisfaction and bottom-line results by reducing variation and waste, thereby promoting a competitive advantage. It can be applied at all places where variation and waste exist, and every employee should be involved.

ISO 9001 Quality Management System (QMS) is a very good generalized system taking into consideration quality assurance and quality control. ISO QMS standards provide guidance and tools for companies and organizations who want to ensure that their products and services consistently meet customer’s requirements, and that quality is consistently improved. This may also be coupled with ISO / TS 16949 for continual improvement.

Statistical Process Control (SPC) uses several basic and advanced statistical methods that to make manufacturing improvements more effective, resulting in products and services that improve value to both customer and supplier. A trade-off analysis helps in realizing if losing one quality or aspect of something in return for gaining another quality or aspect.

The Automotive Industry Action Group (AIAG) has effectively developed tools / procedures for the automotive sector, which helps all companies in this sector to maintain the same procedures and quality. Advanced Product Quality Planning (APQP) developed by AIAG, shown in Table I, is similar to the concept of Design for Six Sigma (DFSS), for product development system [9].

TABLE I. ELEMENTS OF APQP DEVELOPED BY AIAG

Sr. No.	Tools / Procedure	Significance
1	Failure Mode and Effects Analysis (FMEA)	To understand the possible failure modes and their effects in process and in design. (DFMEA & PFMEA)
2	Statistical Process Control (SPC)	To monitor and control a process using statistical methods.
3	Measurement Systems Analysis (MSA)	To evaluate the measuring systems and equipments for variation to eliminate measurement errors.
4	Production Part Approval Process (PPAP)	To validate that the company has developed their design and production process to meet the customer's requirements, by minimizing the risk of failure.

The purpose of APQP is to produce a product quality plan which will support development of a product or service that will satisfy the customer. The three phases in APQP, i.e. development, industrialization and product launch, serves as a guide in the development process and also a standard way to share results between suppliers and automotive companies.

Design Failure Mode and Effects Analysis (DFMEA) is the application of the Failure Mode and Effects Analysis method specifically to product design. It allows the design team to document what they know and suspect about a product's failure modes prior to completing the design, and then use this information to design out or mitigate the causes of failure. The DFMEA is ideally begun at the earliest stages of concept development, and can then be used to help winnow down competing designs and to help generate new, more robust concepts.

On the other hand, a Process Failure Mode Effects Analysis (PFMEA) is a structured analytical tool that can be used to identify and evaluate the potential failures of a process. PFMEA helps to establish the impact of the failure, and identify and prioritize the action items with the goal of eliminating risk. It is a living document that should be initiated prior to process of production and maintained through the life cycle of the product.

The purpose of Measurement System Analysis (MSA) is to qualify a measurement system for use by quantifying its accuracy, precision, and stability. This is because, If measurements are used to guide decisions, then it follows logically that the more error there is in the measurements, the more error there will be in the decisions based on those measurements.

V. CONCLUSION

A systems approach to metal to plastic replacement brings to forth a concrete road map for any industry or any product without getting lost, in the quest for achieving better. As mentioned earlier, the boundary for this system can be set depending on the application of the product, its functionality, strength and mouldability.The three factors that drive metal replacement today are: (i) Cost Out (ii) Performance Enhancement (iii) Product Differentiationor a combinationof the three. Importance of each driver is highly dependent on the market segment [10].

Generally, metal replacement is made when plastics offer equal or better performance at a saving of at least 20 percent in finished part cost [3]. To find the saving, the company needs to define improvements in part performance and costs. Doing so means evaluating the materials, the assembly and manufacturing practices, and the application. In comparing an existing metal part with one of plastic, accounts for all real costs, including finishing and operating costs buried in overhead. Although plastics may cost more per pound than metal they often are less expensive in the finished part due to parts consolidation and elimination of machining operations, among others factors. In addition they also reduce carbon footprint of a company, since plastic part production effectively reduces energy utilization than a metal part production. "Systems approach" as a necessity gives a certain objective; to find ways and means for its realization requiresthe systems specialist (or team of specialists) to consider alternative solutions and to choose those promising optimizations at maximum efficiency and minimal cost in a tremendously complex network of interactions [11]. This, as we have seen in metal to plastic replacement, requires elaborate techniques and obviously the computer systems for solving problems far transcending the capacity of an individual. However the results ultimately benefit the society.

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