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Design for Manufacturing of Electro-Mechanical Assemblies in the Aerospace Industry

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Abstract

Electronic design engineers struggle continuously to obtain a satisfactory trade-off between item performance and cost. On one hand, they would like to employ the best material and components available on the market and opt for time-consuming manufacturing processes in order to obtain high-performance parts. On the other hand, such choice would lead to high recurring cost making the part less attractive in the market. In this scenario, industrial engineering team becomes a crucial industrial entity. It assists the Design Engineers by providing design rules or guidelines. This guidance is intended to provide recommendation to the development team in order to define what is technically feasible and achievable inside an industrial process contest. These rules should not be too strict in order to guarantee acceptable part performance and therefore market attractiveness. The rules contain guidelines on mechanical, process and material aspects. This chapter will focus on design for manufacturing of electro-mechanical parts for the aerospace industry typically being a high-end and high-performance part. Nevertheless, cost and time remain a key aspect to guarantee. The effects of such rules on mechanical and electrical performance will be highlighted and discussed, with a specific focus on high frequency electrical assemblies (1–30 GHz). It will also contain a review on microelectronic production techniques that impact on the part's electrical performance.

Keywords: design guidelines, design for assembly, design rules, aerospace products, avionics, preferred part list, prototyping, additive manufacturing, continuous improvement, six sigma, product manufacturing figure

1. Introduction

Designing electro-mechanical systems in the aerospace industry is a challenging task for many reasons. First, the programs may last decade, so when the design phase starts the design team must envisage how the product will be sustained and maintained in 20 or 30 years on. Second: reliability is a *must* in this sector. They cannot be taken for granted or worse of all avoided by the design team. Possibly, this is the most important feature a design team should address. All these features are typically summarized in what is defined as quality management system (QMS) that are the company's processes that overlook the design and production phases trying to guarantee the respect of such important requests. All this does not come for free,

on the contrary. Guaranteeing and satisfying all these aspects leads to high costs of the engineering and production phase. Nevertheless, engineering and design teams are constantly pressed by the executive board to deliver cost-effective solutions, in time and in-spec.

In this context, the role of industrial engineering teams inside an aerospace company can play a decisive role in delivering the targeted requirements (time-cost-quality).

In order to do so, the industrial engineering team needs to be part of the design team from the beginning, even during offer proposition if needed. Moreover, its requirements, suggestions and strategies must not be seen as secondary or expendable to meet selected electrical or technical specification. On the contrary, if a particular feature needs to be sacrificed during design phase, this should be a technical performance that is not directly requested by the customer or end-user.

During the design flow, industrial engineering can be engaged in two possible ways:

1. In the final design stages to verify that the part designed by the electrical or electronic engineering team fulfills several conditions regarding physical dimensions, materials employed, interconnects, and so on. In practice, the role of the industrial engineering team is to give a “go ahead” or “modify” decision based on the outcome of a specific checklist compilation and know-how of the manufacturing process. In this context the industrial engineering members act as review body rather than participant of the design team. This approach often leads to difficulties when the production of the part ramps-up since some aspects related to manufacturing were overlooked during the design phase.
2. Early on the design stage to recommend manufacturing related views, propose suggestions and identify solutions that would have been probably rejected by a “purely” engineering team.

In essence, design for manufacturing (DFM) is a development & design issue, not a manufacturing topic. “D” stands for design and therefore “DFM” is a design challenge”.

The following sections contain indication on how the industrial engineering team can be effective during the design phase (i.e. implementing best practices for DFM) and in the subsequent production phase in order to proactively sustain and improve the manufacturing processes.

The following terms are often referred to in the rest of the chapter:

- Industrial engineering: a team of people, or a better a division of the company, which is constantly involved in both engineering and manufacturing activities. Its essence is to act as the *trait-d’union* between development engineering and production & operations areas. The team is responsible for representing production requirements and needs in the design team, designing the manufacturing work-flow of the part (work-cell and work-cycle design) and sustaining the part during the entire production time
- Producible/Producibility: the attribute of a part that can be manufactured in a given time and cost constraint thorough industrial repeatable processes featuring a level of quality, for example, compliant with ISO9100 standards.

2. Design for manufacturing production technologies and best practices

The design team should treat manufacturing requests and constraints as a requirement in the same way it tackles the technical requirements posed upon the item under development. Therefore, manufacturing aspects require a design strategy and a verification method.

DFM strategies can be summarized as best practices or design rule. In general, rules can be strict and often are associated with the concept of violation and penalty. An alternative way of implementing the process can be obtained by giving guidelines. The latter are less strict and provide a design philosophy rather than giving strict indications.

An important feature of designing and producing parts in the aerospace industry is that large quantities of the same part to be produced are seldom encountered, as occurs in the consumer market or semiconductor industry. Apart for very specific components, for example, transmit/receive modules inside a phased array, most other parts that compose an electro-mechanical system are usually produced in a scale of a few parts per month or even less.

Trade studies are very important in the aerospace industry. They should be carried out at the beginning of the design phase to identify the most viable solution. It is important to emphasize that the Producibility requirements have the same dignity as the electromechanical requirements expressed technical specifications and the team's objective must be to respect ALL requirements, or identify the most balanced solution among a set of proposed viable solutions.

There are multiple ways to implement a project that fulfills the given requirements and conditions. N alternatives can be identified (a minimum of three is suggested). The decision on which design solution is "best" can be taken using a radar chart type diagram, as depicted in **Figure 1**, which shows the specific requirements and the constraints to be considered (industrial, growth capability, business opportunities and so on). It is useful to subdivide the requirements and constraints into NEED-TO-HAVE and GOOD-TO-HAVE categories.

A typical case study is here provided with the aid of **Figure 1**. The goal of the team is to design a microwave electromechanical assembly fulfilling some electro-mechanical requirements listed in technical specification. Moreover, the part shall be produced within a maximum cost figure (expense of components and labor) and the design cycle shall be less than 12 months long.

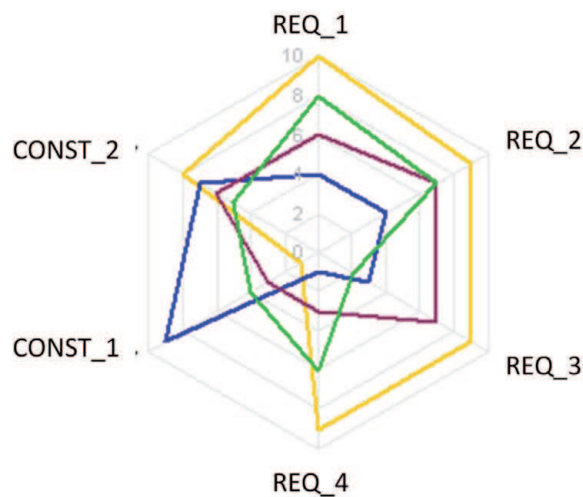


Figure 1.
Radar chart helps understanding design trade options.

Electrical requirements such as gain, noise, signal linearity and DC power consumption can be summarized in REQ_1. Thermo-mechanical requirements, such as maximum temperature of operation and the capability of withstanding certain shocks and accelerations, can be associated to REQ_2. Reliability specifications are considered in REQ_3. The term *space de-rating* is often referred to in aerospace industry to recall the concept that an electrical component can be operated in a sub-optimum electrical condition that reduces the probability of component failure. Finally, cost related aspects are accounted for in REQ_4. Automated assembly greatly influences overall labor cost and shall be also considered when computing REQ_4. On the other hand, automation is a feasible solution when a large quantity of components is to be produced. This is due to the non-recurring expenses associated with the development of automated programs for the specific part. Design time can be considered in CONST_2 while the use of certain component and material to satisfy safety or export prescriptions are considered in CONST_1. An example of safety prescription is REACH requirement applicable in the EU to improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substance. The U.S.A. applies a limitation on the export of components only to specific and approved end-user countries (ITAR, ECCN or EAR99).

The yellow line, in **Figure 1**, appears to be a solution featuring high technical merit but requiring the use of some component that is not compliant with safety constraints or export limitations. This is quantified by the low value expressed in CONST_1. On the contrary, the blue line represents a solution that complies with time and material/component prescription but features low technical merit. The green and burgundy curve represent solutions that suitably trade-off between all requirements and constraints. Some requirements may be in contrast against each other. For example, higher electrical performance may be obtained at the expense of poorer reliability or vice versa. Similarly, demanding thermomechanical requirements can be fulfilled if accepting the higher costs of using advanced materials and extra labor time. Moreover, even within the same set of requirements, for example electrical performance expressed as REQ_1 there might be some conflict. Higher gain and linearity is obtained at the expense of greater power consumption.

Typically, the identified solution will cover most of the requirements leaving unsatisfied only a minimal part. Therefore, the best solution is the one having the largest area in conjunction with no points close to the origin of the radar chart, consequently the burgundy curve in **Figure 1**.

The project manager must work to manage the lifetime risk of the product/program linked to the failure to meet these requirements. In the event of conflict, a trade-off must be made between the electromechanical requirements and those of producibility, privileging the latter especially for series production (items with multiplicity ≥ 5 for one system).

Finally, design guidelines are particularly useful in contexts where most of the assembly is performed manually, whereas rules apply where the process is highly automated and product performance is obtained by-design rather by manufacturing tuning.

2.1 Production technologies and processes

Production of electrical assemblies operating at high frequency requires a set of manufacturing technologies that ranges from packaging to adhesion up to interconnects. The topic is very broad and some aspects are covered in [1]. What is important for this chapter is that several of these processes are manual. While,

on one side, manual assembly can help obtain desired product performance on the other it increases tuning time since the “starting point” can be quite far apart due to the larger variability of manual processes. Moreover, at microwave frequencies, interconnects and adhesives influence electrical performance due to the parasitic effects, and therefore must be taken into account during design phase.

A best practice that greatly aids design for manufacturing topics is the manufacturing organization meeting with design engineers to discuss the latest developments in manufacturing technology. Moreover, the Industrial engineering team should periodically provide a report containing investments and improvements foreseen in manufacturing over the following 2–3 years. In this way, the company and the engineering team are well aware of advances in manufacturing and can profitably orient design choices in the future.

2.1.1 Packaging, adhesions and interconnects

Packaging: Kovar is used to match the expansion of alumina or similar ceramics, and is typically used as a carrier for microwave integrated circuit substrates of these materials. If it forms part of the ground plane it is usually plated, or it may be plated to allow soldering or brazing to the ceramic. Kovar is used for small carriers since its density is higher than Aluminum and therefore not advised for large packaging where the overall weight can become too large. On the contrary, Aluminum, thanks to its smaller density is used for the overall packaging.

Adhesion: plays an important role in microelectronics since it provides simultaneously electrical grounding and mechanical bonding. Adhesion at integrated circuit (IC) level can be performed thorough epoxy attach (gluing) or eutectic die attach (brazing). Let us analyze pros and cons of each method.

Eutectic die attach (brazing) is a highly controlled die attach process for high reliability, high accuracy, and high performance devices. To achieve high yield, sophisticated heating and cooling mechanisms are employed. This means controlling that the device heats and cools according to a very strict parameter line. The essence of a eutectic reaction is going from liquid to solid, using eutectic heating and cooling. Eutectic alloys for soldering are composed of Sn (tin), Pb (lead), Ag (silver) and Au (gold). When different metals are combined into alloys, a range of melting temperatures are created with varying proportions of each metal used: AuSi@363°C, AuSn@280°C. The advantage is a very high conductive (thermal and electrical) adhesion obtained at the expense of a manual and very complicated processes (a few seconds or degrees difference in the brazing oven could mean success or failure of the process). **Table 1** reports key attributes of alloys for brazing

Alloy Family	Features	Composition	Melt temp. [°C]
SnPb	Typically used in surface mount assembly. High bond reliability.	Sn ₆₃ Pb _{36,7} Sb _{0,3}	183
		Sn ₆₀ Pb _{39,7} Sb _{0,3}	183–188
		Sn ₆₂ Pb ₃₆ Ag ₂	179
In	Elastic interconnect	In ₁₀₀	156.7
		In ₅₀ Pb ₅₀	180–209
AuSn	Strong bond strength. Excellent thermal and electrical conductivity.	Au ₈₀ Sn ₂₀	280

Table 1.
 Attributes of several alloys for brazing.

microelectronic parts. Important parameters to drive the choice in microelectronic components are the electro & thermal conductivity (to determine in-package device electro-thermal performance) and melt temperature (that implies manufacturing complexity). Gold-Tin alloys (Au/Sn) are typically employed in assembly of microwave devices while Tin-Lead (Sn/Pb) is preferred for the production of digital boards.

Tin/Lead (Sn/Pb) based alloys are the most commonly used alloys for welding on copper, nickel or silver surfaces. The addition (optional) of a small percentage of antimony prevents the transformation of the tin (beta) phase into a tin (alpha) phase called “tin plague”, with a reduction in the volume of the alloy mass and a drastic decrease in the mechanical strength of the welded joint. Silver is added to allow soldering on silver surfaces without causing the alloy to over-dissolve the plating metal. All tin-based alloys are strongly discouraged for welding gold surfaces, due to the rapid dissolution of gold in the alloy (scavenging).

Indium-based alloys are particularly useful due to their great ductility, which attenuates or eliminates failure problems resulting from fatigue failure of welded joints, and by the lower solubility of gold in such alloys. About 1% of gold must dissolve in an indium/lead based alloy before the AuIn₂ solid phase can be formed, which is stable in equilibrium with lead up to 319°C and acts as a barrier, limiting the further dissolution of gold: a thin film of gold can withstand for 15 minutes in an In₅₀Pb₅₀ alloy bath.

Gold/Tin (Au/Sn) alloy is specifically used to weld gold surfaces without having to use flux, due to the high gold content it contains. It is normally sufficient to use a nitrogen-based inert atmosphere during the process. This alloy is able to dissolve gold in considerable proportions (up to 1–2 microns in thickness) during a normal welding cycle lasting a few minutes, which requires that the surfaces to be gilded have a thicker plating, i.e. at least 3–4 µm.

Epoxy attach (gluing), on the other hand, is a far more easier manufacturing process than brazing. It can be very often automated and the time constraints/temperature constraints of the process are much less critical than brazing. Usually the devices is cured for 30 minutes inside a curing oven at 120°C. Nowadays, silver-loaded epoxy adhesive with high thermal and electrical conductivity are available whose electrical and thermal performance are not far from the ones obtainable with chip brazing.

Interconnects: are the electrical connections between semiconductor devices such as integrated circuits or transistors and the first level of packaging. The most familiar and widely used First-Level Interconnect (FLI) is the wire bond. Wire bonds are available in several types, such as ball bonds, wedge bonds, and ribbon bonds, each with unique variations. The typical wire bond for high-end applications is a wire bond is formed using a gold wire that is typically 25 µm diameter, though high-volume commercial systems at lower frequencies use aluminum wire bonds with diameters as large as 54 µm.

The purpose of the wire bond is to create an electrical connection between an IC and some type of conductor, typically a metal trace. At lower frequencies the wire bond performs as a simple electrical contact between points and is specified at a maximum current handling. However, as frequency increases, wire bonds begin to perform as inductors. The requirements on the wire bond increase as frequency is increased. Typically, the length of the wire is limited to reduce inductance. Also, the shape of the wire bond is specified and in some cases manual accomplishment becomes unavoidable. **Figure 2** depicts the equivalent electric circuit and the corresponding parasitic reactance and resistance as a function of frequency of a 1 mm/25 µm diameter wire bond. As frequency increases, the parasitic effects

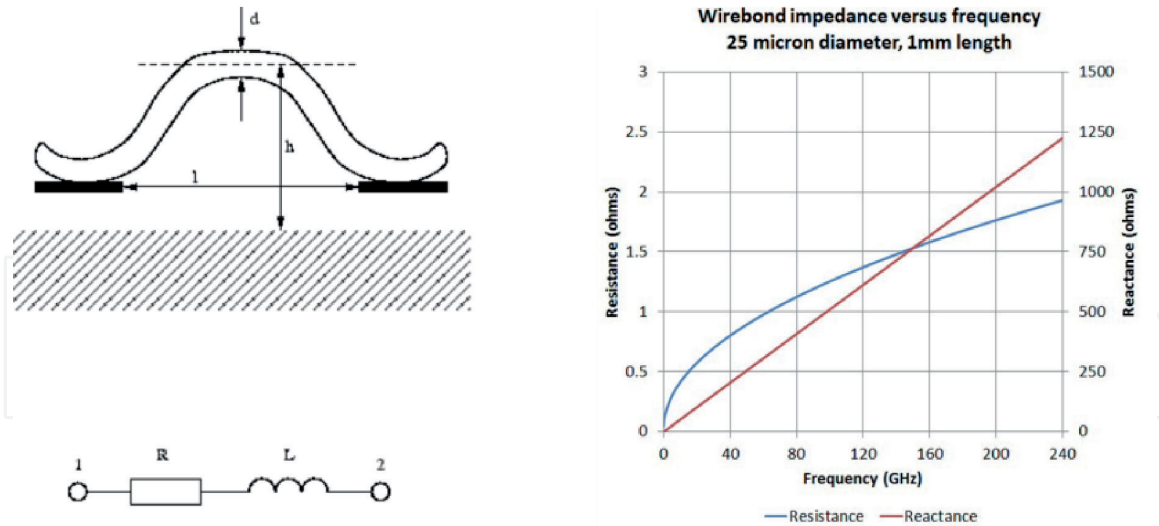


Figure 2. Bond wire simplified geometry and equivalent circuit (left) and impedance vs. frequency (right).

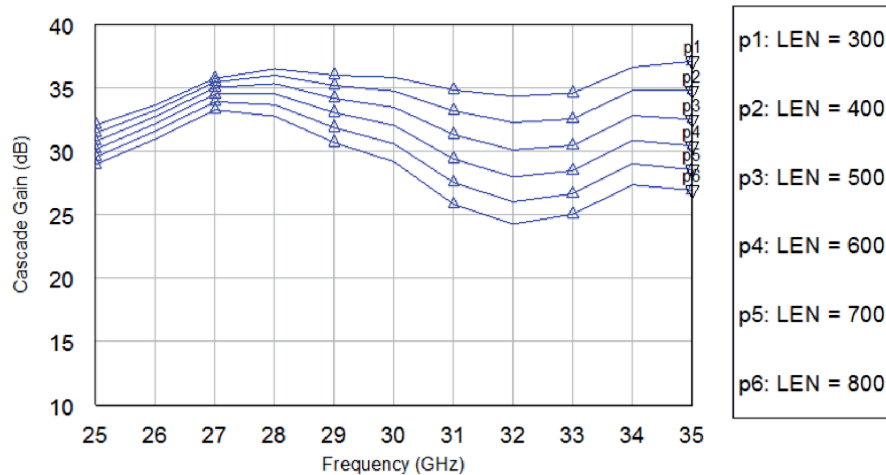


Figure 3. Bond wire length effect on a RF chain around 30 GHz.

become large and can be compensated only by decreasing wire length, and sometimes operator skill becomes mandatory.

The effect of wire length, and therefore inductance, on a high frequency circuit is demonstrated in **Figure 3**. A simple RF chain, composed by a cascade of two amplifying stages, is considered. The two amplifiers, in Monolithic Microwave Integrated Circuit (MMIC) technology, are connected to rest of the circuit through a pair of wires at the I/O ports respectively. The length of each wire is controlled by a variable “LEN” and is swept from 300 to 800 μm .

The gain is rather flat for LEN = 300 μm (highest curve, marker P1), while it becomes quite rippled and gain drops for LEN = 800 μm (lowest curve, marker P6). Consequently, length of bond wires should be carefully controlled. Occasionally operator ability is essential to obtain the desired electrical performance.

Wire bonds can be connected using ultrasonic bonding, thermos-compression bonding, and thermosonic bonding [2]. Ultrasonic bonding uses pressure and ultrasonic vibrations from a bonding tool to create the bond between the wire and the metal surface. Thermo-compression uses pressure from the bonding tool and high temperature to create the bond. Thermosonic bonding combines ultrasonic and thermos-compression methods to create the bonds.

2.1.2 Automatic vs. manual manufacturing

The choice of manual or automatic assembly is driven by some parameters. First is the electrical and thermal requirements. In some cases, the requirements could be so stringent that only a manual process is capable of performing a very fine-tuning. For example, when temperature and heat dissipation are critical, then brazing can become the only acceptable solution. The effect of interconnect parasitic were also discussed, in the previous Section 2.1.1, and how operator support can become decisive to obtain acceptable performance, especially at GHz frequencies.

Another parameter to be accounted for is the number of parts to be produced in 1 week, 1 month or 1 year. This number plays a crucial role. If a mass production is foreseen, then manual assembly is not advised due to the lengthy and costly process associated with it. On the contrary, when very few parts are to be produced then manual process is acceptable, also because automatic assembly requires the development of programs and codes with the consequent Non Recurring Expenses (NRE) for developing them.

2.1.3 Additive manufacturing in the aerospace sector

The paradigm of design for manufacturing can be found in Additive Manufacturing (AM) technology. AM represents a key example where an advancement in production technologies enables new engineering concepts that can come to life *only* with this technology. In this sense, it is quintessentially a design *enabled by* manufacturing.

In the aerospace sector, AM is applied mostly on metallic parts (Aluminum, Steel, Titanium and related alloys) rather than composites (plastics) as occurs in the consumer industry. In fact, the initial investment in terms of machinery and training is very high and must be carefully accounted for in the business model.

AM in aerospace has been happening for some time now with many applications, covering everything from the creation of aircraft or helicopter parts, making lighter and more efficient engines, 3D printed turbines etc. 3D technologies generally save on time, money and create stronger, lighter, and more efficient finished products [3].

An example of AM technology and process applied to the aerospace industry is shown in **Figure 4**.

The part itself is not very complex, but it proves how AM can be gainfully exploited to create lighter or more complex structures than the ones previously realized with “prior” technologies.

One of the challenges of the market is the restriction of the volume of construction and the size of the product. An aircraft is made up of very large components and additive manufacturing is today limited to the volume offered by the 3D printer. Most technologies offer solutions with limited print volume, making 3D printing applicable only to small components. So, this constraint that could slow down the growth of the market. Even if so, today’s 3D technologies have already made it possible to create and qualify fairly large (approx. 30 cm) components for space [4, 3] and aviation [5]. Finally, the latest available machines (SLM500, Concept Laser Xline 20000R, EOS M 400) are capable of building even larger pieces.

2.2 Design rules and design guidelines

Design rules can be seen as a set of physical, geometrical, chemical, mechanical limitations. They are very useful when the manufacturing process is constant and

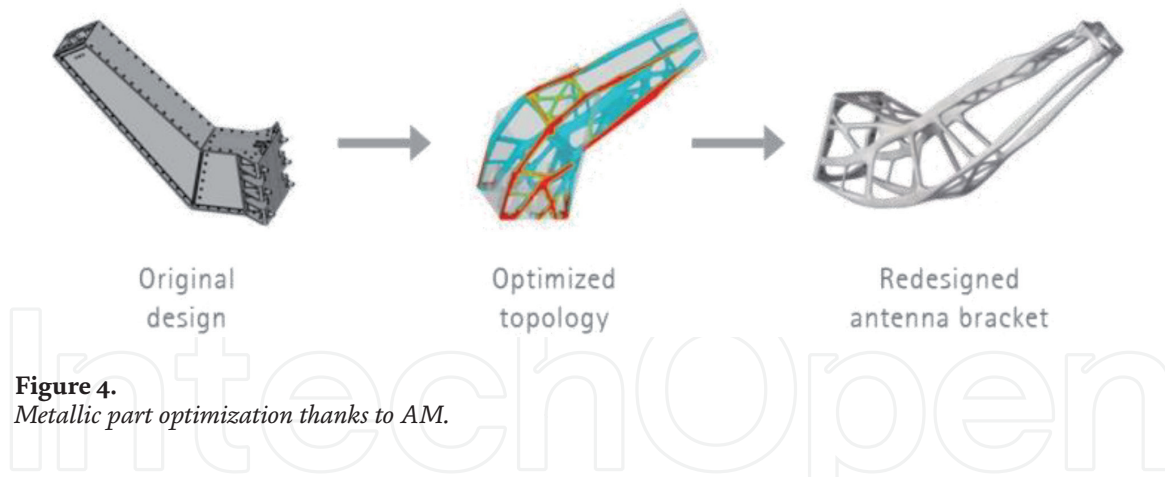


Figure 4.
Metallic part optimization thanks to AM.

repetitive as happens in the semiconductor industries or in large scale production. This paradigm however is less stringent in the aerospace industry since there is not a mass production of items, but on the contrary, a production of a large quantity of different parts each one characterized by very small multiplicity. Moreover, while digital board assemblies can follow rules developed for the consumer market, high frequency microwave assemblies (operating at 100 MHz–30 GHz) are typical of the aerospace industry and suffer from less standardization. Consequently, for the latter guidelines rather than rules should be applied.

Anyhow, rules and guidelines should address the following features that are critical in any industrial manufacturing process:

1. Designing parts for “modularity”, i.e. a module is a self-contained component that is equipped with standard interfaces that allow it to be integrated into a larger system. Modularity has several benefits: the product is easy to assemble/re-assemble and most of all, in complex systems, it aids to detect quality problems or non-conformities
2. Designing parts to compensate for process statistics and yield, component and material deviations
3. Ensure the product can be assembled and manufactured using standards processes, i.e. identifiable and written in a production document or drawing without requiring ultra-specialized capabilities or different production approaches for each realized component.

2.2.1 Design rules

Design rules are written to suit a specific production technology. In the electronics for aerospace industry important production technologies are microwave modules and digital boards.

Digital board production uses rules similar to the ones developed for consumer and telecom products, always taking into account that aerospace industry produces a relatively small amount of high-performance products as opposed to consumer market. Anyhow, well known standards can be applied, for example the IPC-2291 “Design Guideline for Printed Electronics” or IPC-2252 “Design Guide for RF/Microwave Circuit Boards” considering class 3 for the aerospace industry.

On the other hand, production of complex microwave parts is very typical to the aerospace & defense sector and seldom finds application elsewhere. This is related to the high cost involved in development and production. Design rules for these objects often end up as a few set of geometrical rules. An example of design rules

applicable to hybrid microwave modules or hybrid microwave integrated circuit is given in the following:

- Package dimension not to exceed a certain value so that the part can be manufactured using automatic assembly machines
- Minimum distance between adjacent components, so the part can be assembled using automatic *pick'n'place* machinery.
- Maximum dimension of materials and substrates to avoid cracking due to thermal expansion/compression
- Metallisation and finishing of surfaces
- Geometrical rules regarding thickness, angles, corner radius, shapes, etc.

2.2.2 Design guidelines

Design guidelines provide indications on how to deliver a *design for manufacturing* solution, rather than giving rules and consequently a PASS/FAIL decision. They can be seen as indications that the Design team has to follow in order to design a producible part.

While rules provide a PASS/FAIL criteria, often regarding geometrical or mechanical properties, guidelines provide assort of “sensible” indications so that the design has a higher probability of success. In other words, if the guidelines are followed, very limited manufacturing issues are expected later on. On the contrary, if the design team decides not to follow the guidelines, plenty manufacturing issues during the production stage should be expected.

A typical design guideline could be to avoid overcomplicating the electrical schematic, eliminating unnecessary components. Every component placed inside the schematic should answer to at least one design goal (typically performance, testability or reliability). If a component does not contribute to at least one of these “high-level” design goals, the engineering team should substantiate the reason for which it has inserted. Boothroyd and Dewhurst [6] suggests, among other topics, that unnecessary parts are those that answer “NO” to the following questions:

1. Does the part move relative to other parts in normal operating condition of product?
2. Is it necessary that the part is made of different materials or isolated from other parts such as electrical insulation, heat insulation, or vibration reduction?
3. Does the part have to be isolated from other parts otherwise it is impossible to assemble the products?

If the answer to all questions is “NO”, the part is unnecessary and can be integrated with other parts.

Another guideline could be to design parts so that final performance can be obtained after tuning or programming performed in reasonable time and most of all avoid using components (or electrical schematic) so that the overall module performance resides on a specific component of the module. In this case any shortcoming of the component will affect one-to-one the module’ behavior.

2.2.3 Prototyping, virtual or real (fast)?

Design engineering team, during the initial design stages, would like to have an initial prototype to test the idea and verify in-lab any limitations that commercial CAD simulations or analysis are unable to predict.

Basically, there two types of prototyping techniques: virtual or real (fast).

Virtual prototyping relies on very accurate model-based CAD simulations. The models are often validated through a previous trial-error-correct cycle. The method is relatively inexpensive, can be very fast and deliver accurate results providing the model itself is accurate.

Additive manufacturing technologies (metal and plastic) provide fast turn-around time to realize real and fast breadboards. In this case, the prototype is real, the time constraints are guaranteed but the exercise can be expensive, compared to virtual.

The choice between real or virtual prototyping can be performed by analyzing the following parameters:

1. Virtual model accuracy
2. Available time and budget constraints
3. Associated Risk mitigation

If parameters 1 and 2 have higher weight then virtual prototyping appears to be the appropriate solution. On the contrary, if design uncertainties are high and risk mitigation is necessary, then real prototyping becomes useful.

2.3 Preferred part list

The objective of a preferred part list (PPL) is to direct the user toward a limited number of component types, covering all design applications. The aim is to avoid duplication and achieve cost reduction and procurement effectiveness [7].

Consequently, you should identify a subset of typically used components to generate your custom PPL. Components belonging to the PPL should be employed “by default”, and any derogation from the list should be clearly explained and technically justified.

Definition, creation and sustainment of a PPL should be a company-funded activity and the client-related programs receive the benefit. Like any other engineering effort, the more work put in the initial stages, the less work is required on final stage.

Initial cost is only one consideration for the PPL and is compensated by the value gained over the lifetime of the product (procurement, production and maintenance). Since the cost of introducing and sustaining a PPL in a company is rather relevant at the beginning such choice must be willingly enforced and sponsored by the company’s top management (director general and director of engineering). Moreover, the director of the purchasing department has to be actively involved, since he might be tempted, over a short-term period, to prefer cheaper or readily-available parts as an alternative to the parts in PPL.

Components shall be introduced in PPL after analyzing the criteria listed in the following.

Performance history: actual field experience or extensive relevant testing.

- Accessibility: parts that can be purchased from multiple sources, (vendors or/ and distributors).
- Alternating source: same form, fit, and function for parts, but different manufacturers' names and part numbers. (Different manufacturers' crossover part numbers must be equal.)
- Regulatory compliance: RoHS/REACH.
- Reliability figures: mean time to failures (MTTF) or mean time between failures (MTBF).
- Screening: favor pre-screened or tested parts.
- Life span: favor parts with higher Shelf life.
- Economic order or lot quantity: Consider minimum buy.
- Lead-time: consider cost vs. the desired lead time trade-off.
- Bring the strategic suppliers on board the PPL project

Considering the main stages in the product's life-cycle (from concept to maintenance), the possible savings in each phase are examined:

- Research and design: Excluding a newly introduced component's unknown performance will accelerate design validation and testing efforts. Shorter development cycles realized through less component failure issues and time taken for trouble-shooting and reworking breadboards and prototypes. Quicker proof-of-concept results. Parts used from PPL are more likely to be available, and small development quantities can be ready at-hand.
- Purchasing: Material planning is more stable making part procurement less challenging. Strategic suppliers are encouraged if they are actively involved in the company's PPL project.
- Manufacturing: Less line failures using proven parts. Assembly personnel already very familiar with part handling requirements and issues.
- Customer Support: Fewer returns and higher reliability. Practice with frequently used parts promotes a deeper understanding of part behavior and common failure mode and symptom identification. Customer satisfaction with longer life product and fewer returns, and fast turn-around time in repair.

The design engineer who selects the components must choose as many parts as possible from the PPL. Ideally >80% of the bill-of-materials (BOM). By selecting even a majority of the parts from the PPL, the benefits realized from the arguments presented above should be sufficient to encourage the company to validate and enforce the practice of using a PPL.

Finally, it is obvious that the PPL should be created and managed by the Industrial engineering people who are the stakeholders of the activity. In fact, PPL has an impact on all phases of the product life-cycle. The size of PPL depends on the complexity of the typical system the company develops. For an aerospace

company that designs and manufacture avionic systems (radars, electronic warfare, satellite payloads) the size of PPL could be around 2000–3000 components.

2.4 Design for reliability, maintenance and test

As stated many times previously, aerospace products feature high system complexity, and must provide high-performance to be delivered over time and in harsh environment and operating conditions. Consequently, the design team must take into account these aspects when designing the product. Design for Reliability, Maintenance and Test (RMT) is often referred to as design for RMT as if it were a single topic. However, different strategies are employed as clarified in the following to separately guarantee the three topics.

2.4.1 Design for test

Design for test is a crucial aspect to guarantee the part can be efficiently produced during its life-cycle- The part must be designed so that it's key features and characteristics are accessible and verifiable during production test. Keep in mind that in the aerospace industry, practically 100% of the realized parts are fully tested, often over temperature and in mechanically stressful condition (vibration or similar), to verify they are fully compliant to specification and free from manufacturing defects. Moreover, the test is functional and not merely structural. Manufacturing functional tests are carried out to verify that the part is working and function as expected and not just assembled correctly. Functional test on 100% realized HW parts is typical of the aerospace industry to guarantee performance and reliability of manufactured parts and is less applicable to consumer products due to the very high time and cost involved in these kind of test. Finally, aerospace modules that fail the first manufacturing test need to be analyzed and tuned so the part meets the technical specification. Given the time and cost involved in the assembly process, it is illogical that the part should be discarded if the first production test fails. Consequently, designing parts for testability greatly aids the troubleshooting phase, ensuring production people can speedily identify the shortcoming and restore the part.

Given this scenario, it is mandatory that the design team keeps into account these aspects when designing the part. The principle is to add components and interfaces to make it easier to develop and apply manufacturing tests to the designed hardware. At the same time, test engineering department should be consulted in the design phase, so they can bring provide advice and most of all start designing the Automated Test Equipment (ATE) that will be used in production phase but could also be used by the engineering team for product verification and validation. The idea underlying design for test is: Pay less now and pay more later without DFT.

2.4.2 Design for reliability and maintenance

Design for reliability is crucial aspect in the aerospace industry, where reliability is a must considering the mission criticality of these systems [8]. Reliability somewhat depends on the assembly process employed. One indication is to avoid those manufacturing processes that are less repeatable or controllable.

Design for maintenance shared some requirements with design for test, since any maintenance activity starts with identifying the part in failure within the system. Other aspects consist in the designing the parts in a modular way so any failed item can be easily replaced without having replace the entire system or sub-system,

3. Production sustainment

Information and guidelines were provided in the previous section so industrial engineering can proactively contribute in the design team giving correct priority to manufacturing requests. While this activity strongly mitigates manufacturing risks in production stage it does not totally eliminate risks and therefore some process needs to be applied also during product manufacturing life-cycle.

Open literature refers to these processes in many ways: lean manufacturing, six sigma, continuous improvement, kaizen methods, PDCA cycle, and so on [9–11]. Each method has its uniqueness but, fundamentally, they consist in constant proactive monitoring of the manufacturing process to identify deviations in early stage, introduce improvements, observe the expected result and, if the outcome is positive, standardize the new method.

3.1 Continuous improvement and associated methods

Continuous improvement can be obtained by recurrently applying the PDCA cycle to those product and process that demonstrate an intolerable defect rate or more generally deviate from the desired quality/cost/time target.

PDCA cycle consist in performing four steps as graphically visualized in **Figure 5**.

The first step (*plan*) consist in clearly defining what is the “problem” and consequently the expected result (objective) at the end of the process. The Pareto principle can be applied in order to prioritize the (unfortunately) many issues that might be occurring in Manufacturing.

The second step (*do*) is possibly the most challenging for the industrial Engineer. The goal of this second step is to identify the Root causes that prevent the product/process being on-time, on-cost and in-quality. Many problem-solving techniques can be applied. An example shown here is the Ishikawa diagram **Figure 6** that can be very useful since it helps clustering into smaller sub-problems, which become more easily addressable.

Ishikawa “fish bone” diagram method consists in analyzing all pertinent areas and sub-areas of a typical manufacturing process. When a quality issue arises, the industrial engineering team is notified in order to identify the root-cause of the issue and consequently propose a corrective action. This is not a simple task since there are many areas and factors to be investigated. Moreover, some of the production processes and materials may come from tier 1 suppliers and therefore occur outside the company.

Common production issues in the aerospace industry occur when information related to a specific production process is not fully written but relies on the skill of advanced operators. Therefore, a strong practice is to provide very detailed assembly instructions so that lesser skilled operators can produce the part in high quality standards.

Some issues may sometimes occur when the purchasing department, to obtain cost saving, procures a component or a material from a different supplier claiming it is equivalent form, fit and function (FFF). Rarely this is a painless change since there are always some small differences between two components identified as equivalent FFF on to the other.

Environment parameters (temperature and humidity) are rarely a cause of manufacturing deviations since the assembly process is typically carried out in clean rooms or at the least humidity/temperature controlled areas. In the aerospace industry, final assembly is performed in the company while lower level components

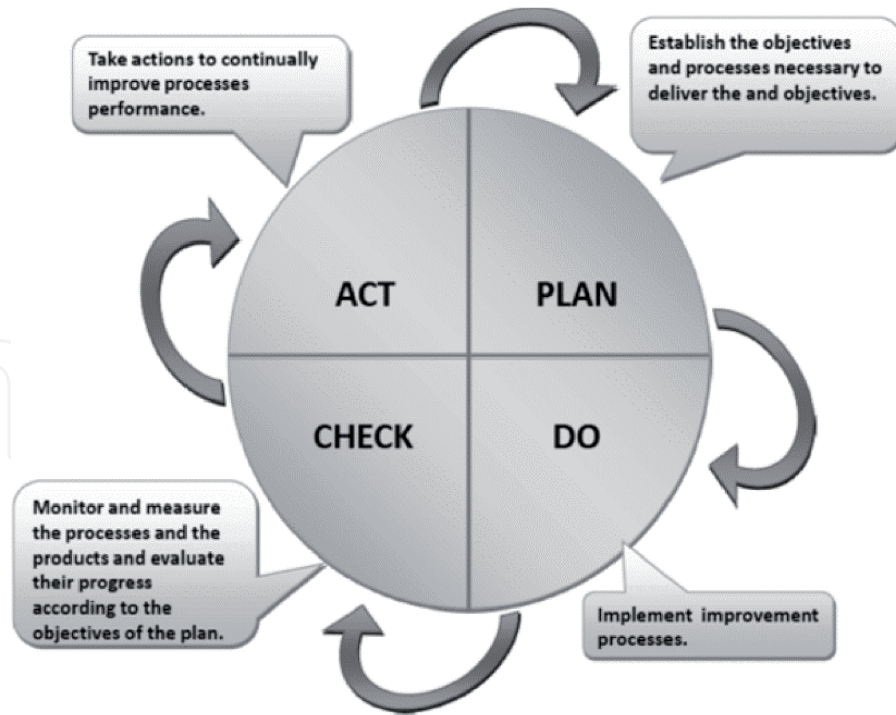


Figure 5.
 Plan-do-check-act cycle.

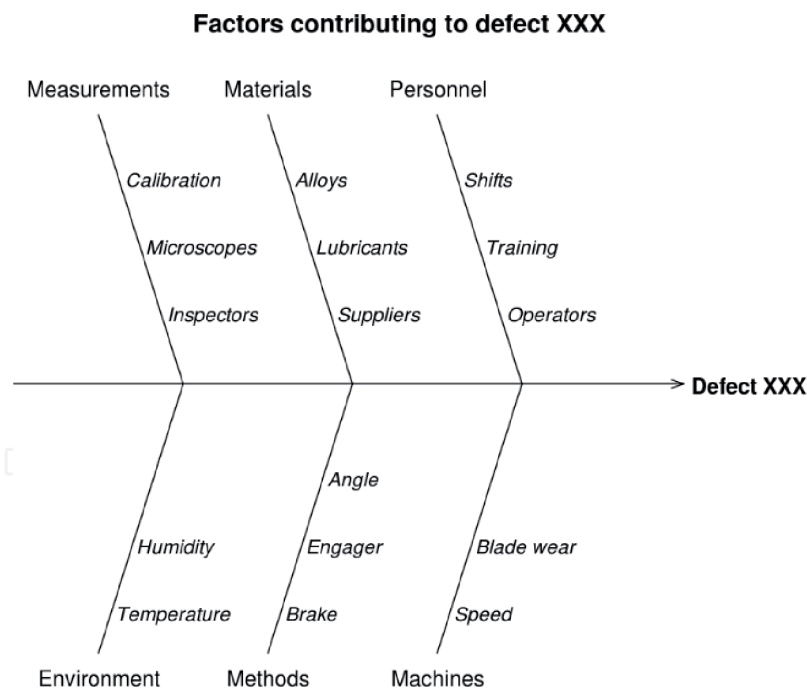


Figure 6.
 Ishikawa "fish bone" diagram useful for problem solving.

and sub-systems may be procured from an external contractor. The same holds for some non-critical services that are occasionally outsourced. Consequently, in some cases, the investigation needs to be performed at tier 1 supplier level too in order to investigate and identify the root cause of the problem.

The final two steps are *check* and *act*. In practice, what has been identified and proposed in the previous two stages needs to be validated and standardized. In all steps, it is important to be un-biased and all problem inputs should be data-driven.

In this context, systems for tracing non-conformities are vital so the create an effective and populated database.

W. Edwards Deming's famous quote is therefore a cornerstone of this problem solving technique: "Without data you're just another with an opinion".

Another practice that contributes to improve product/process performance are manufacturing and engineering organizations periodically reviewing quality non conformities to determine if engineering changes are required. Creating dedicated interdisciplinary teams to perform a specific improvement project is also useful.

3.2 Product manufacturing sheet and figure

As stated previously, all process/product monitoring and the consequent PDCA cycle should be data driven.

A Product Manufacturing Sheet is useful from which a Product Manufacturing Figure (PMF) can be calculated. The sheet and figure are living documents and figures, in the sense that they must be periodically updated to monitor the improvement of a certain production product/process.

The Product Manufacturing Sheet contains structured information regarding its three macro-topics: design, manufacturing and purchasing.

- DDP (design data package): specification, engineering drawings, data libraries, SW code, design rationale documentation, test planes, are available. List of major engineering changes ongoing, if any.
- MNFR (Manufacturing and workmanship): are all the Tooling/machinery available? Personnel has been trained for the specific product? Automatic test equipment – if necessary – is available? Screening procedures are in place?
- SC (SUPPLY CHAIN) quantifies on-time and on-quality purchasing of the major "buy" items that constitute the product, any obsolescence, vendor rating of the key components.

The Product Manufacturing Figure (PMF) is calculated, as indicated in Eq. (1), by summing the three previously mentioned factors, each having a weight (α , β , and γ) proportional to the importance the company gives to each factor.

$$PMF = \alpha * MNFR + \beta * DDP + \gamma * SC \dots \alpha = \frac{1}{2}, \beta = \frac{1}{4}, \gamma = \frac{1}{4} \quad (1)$$

The PMF is computed in the following way:

1. At first, the weight is set for each e parameter (the sum of the weights must be unitary). In Eq. (1), for example, $\alpha = 0.5$, $\beta = 0.25$, and $\gamma = 0.25$. These weights shall remain constant all over the production process.
2. A figure between 0 and 100%, according to a checklist, is computed for each parameter (MNFR, DDP and SC) in Eq. (1). This figure changes in time as the three topics improve (or worsen). Checklists become handy to substantiate the figure—between 0 and 100%—associated to each parameter. Moreover, Quality Notifications can be used to obtain useful information of product non-conformities.
3. Consequently PMF is calculated.

PMF close to 100% indicates the part can be fully produced on-time, in-spec and on-quality. Lower values indicate that you should expect some contained derogation of one of the three parameters. PMF < 40% indicates that the product is not enough for mature for an Industrial-grade production and important improvements have to be applied to one or more of the three parameters. Furthermore, PMF is a *living* index, since it can be computed periodically to register changes in the three parameters. For example, MNFR could improve after a set of tooling is made available or SC worsen if a component becomes obsolete.

4. Conclusions

Evidence so the Industrial engineering team can proactively contribute to designing parts and address manufacturing issues during the design follow is provided. In this chapter, the starting point is deep knowledge and understanding of the critical technologies that apply to each manufacturing process and their impact on product assembly and performance. Once the technologies have been considered, the key-points Industrial engineering team must engage are: involvement from the early stages, definition of rules and guidelines for manufacturing.

Occasionally, the prior activities are not sufficient and some product improvement must be carried out during the production process. Specific continuous improvement activities (PDCA cycle) and also detailed tools and figure to quantify “design quality” in manufacturing have been provided.

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