Pilatus PC-12 Assembly Line: Industrialization, Manufacturing and Process Improvement

Raúl Diego Guichón Aguilar
Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal

Introduction

This study is based on a real case, the Pilatus PC-12 assembly line.
As major aircraft original equipment manufacturer (OEM), Pilatus Aircraft tends to focus more on systems integration. As a result of this approach, manufacturing services are subcontracted to tier-one companies, such as OGMA Aerostructures, which produces the Pilatus PC-12 green aircraft.
A tier one company is the most important member of a supply chain, supplying components directly to the original OEM that set up the chain. Creating a tiered supply chain is part of supply chain management. Its aim is to link important business functions and processes in the supply chain into an integrated business model.
Tier one companies are generally the largest or the most technically-capable companies in the supply chain. They have the skills and resources to supply the critical components that OEMs need and they have established processes for managing suppliers in the tiers below.
In this case, tier one company provides a manufacturing service for the OEM, leaving the OEM to concentrate on final assembly, design and support engineering and marketing.
Tier one companies develop close working and business relationships with OEMs. Both organizations recognize the value of collaboration to improve quality, eliminate waste, cut costs and reduce lead times.
The main objective of this study is to analyze industrialization and manufacturing processes and applicability of state-of-art optimization techniques for those processes.

OGMA Aerostructures

OGMA is a supplier of integrated solutions to OEMs and a first tier supplier, committing to the Aerostructures market for over 30 years. As a full service provider OGMA is able to deliver Aerostructures assemblies and sub-assemblies, either from metallic or composite materials, covering a broad spectrum of Aerostructures family products.
Approved by EASA (European Aviation Safety Agency) as POA (Production Organisation Approval), Part 21, Sub-Part G, its technical competence, quality and performance allow OGMA to deliver on-time, low risk competitive solutions with a broad portfolio of major players in the global aviation market.
The Pilatus PC-12 program started at OGMA's facilities in 1994. Nowadays, the PC-12 green aircraft is entirely assembled at Alverca's facilities.

Pilatus PC-12 Program

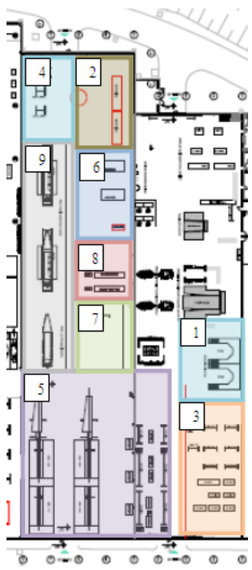
Over 1200 PC-12s have been delivered world-wide as at the beginning of 2014.
The PC-12 is a pressurized single turbine powered by a Pratt & Whitney PT6A-67B turboprop engine utility aircraft, which operates up to 30,000 feet and 250 knots as it is takes off from or landing on very short dirt runways. It has the range to fly six passengers up to 1560 NM, or the ability to fly one and a half tons of cargo over 400 nautical miles with IFR reserves. Maximum certificated passenger capacity is nine in the airline configuration, or eight in the optional executive configuration. The aircraft is unique in its class in that it has both a forward air stair door for passengers and a powered rear cargo door.
Pilatus Aircraft continuously improve its products, and, as part of that effort, introduced the Next Generation PC-12 at the end of 2007.

Parts and assemblies of PC-12 Program
The Pilatus PC-12 structures produced by OGMA are shown and listed below:

1-Wings
2-Fuselage
3-Dorsal fairing
4-Vertical Stabilizer
5-Rudder
6-Ailerons
7-Flap fairings
8-Ventral fairing
9- Doors
10-Harnesses
11-Flaps

Fig. 1 – Pilatus PC-12. *Courtesy of OGMA*

Pilatus PC-12 Production Line
The PC-12 assembly line is located inside a multi-program plant, where several aerostructures are assembled. The Production planning and the Plant Layout enables to manufacture up to five different aerostructure programs within the same plant: EH-101 tail assembly, Pilatus PC-12 green aircraft, Dassault Falcon Pylon, ADS C-295 Central Fuselage and Embraer KC-390 Central Fuselage. The PC-12 assembly line is composed by 8 main different stages, where 13 structures are manufactured: cockpit, floor, rear fuselage, fin (including rudder), wings (including flaps and ailerons), sidewalls (RH and LH), rooftop, fuselage and doors.



1-Cockpit
2-Rear Fuselage
3-Sub-assemblies
4-Doors
5-Wings, aileron and flaps
6-Sidewalls and floor
7-Cabling
8-Rooftop
9-Fuselage integration

Fig. 2 – Pilatus PC-12 Production Line, FMT Layout. *Courtesy of OGMA*

Aerostructures Industrialization

Industrialization of aircraft manufacturing products includes a set of activities of engineering, logistics, quality, scheduling, production and process control, focused on ensuring production according to applicable regulations. Manufacturing is a process consisting in converting raw materials, components or parts into finished goods that meet customers' specifications.

Industrialization process
The industrialization process is started upon Customer PO (purchase order) issuance with provision of the applicable technical data [1].
The activities constituting the industrialization process are:

- Receiving technical data
- Analysis of technical data
- "Make or Buy" analysis and decision
- Tool and jig design and manufacturing
- Process certification
- Defining engineering product structure
- Defining manufacturing product structure
- Creation of Items, Bills of Material and Production Routings
- Intermediate and Final Inspection
- Material procurement
- Realizations of FAI (first article inspection) product
- Manufacturing Product Handling, Storage, Packaging and Shipment
- Support or Post-industrialization phase
- Industrialization management

Configuration management
Configuration control of aircraft manufacturing products guarantees that the current product configuration is updated and the applicable technical data are available at all times throughout the process. This activity does not apply to configuration changes of the product itself, since these are the responsibility of the project owner.
Configuration control of aircraft manufacturing products is limited to:

- Control of product related technical data changes/revisions

- Implementation of changes in the support technical data and in the productive process
- Verification of change and implementation in product

Aerostructures Manufacturing

1. Process Engineering

Once the industrialization process finishes by the complaining of the FAI (first article inspection), the manufacturing process begins. At this stage a set of actions are implemented:

- Process improvement, in terms of operations sequencing, timing and methods
- Implementation of customer modifications, after analysis and engineering product structure definition
- Production support actions
- Process engineering is responsible for nonconforming product, process support during manufacturing, process improvement, manufacturing products management, technical documentation, manufacturing modifications implementation, timeframes and methods engineering, production resources training, subcontractors support and tooling.

Nonconformance product

During the manufacturing process (support phase), it is required analyzing and solving product nonconformities generated by the manufacturing process, as well as implementing required corrective actions. Nonconforming product attributions of engineering are: analyzing and solving the product nonconformity occurred during the manufacturing process (excluding MRB activities)[2], creating the required disposition and identifying improvement opportunities, implementing corrective activities according to customer's requirements, evaluating nonconformities impact, implementing the required corrective actions, analyzing the repeated nonconformities reported in RAC's and promoting new improvement opportunities and ensuring the right implementation of corrective/preventive actions after the PAC/P release.

Industrial Engineering

Specific programs of improvement are required for manufacturing, such as time and costs reduction, reduction of process parameters variability and quality improvement. Consequently, Continuous Improvements plans are implemented (PMC) after requests for continuous improvement (PMP's). PMC's are mid/long-term plans, which resolution and implementation takes time and additional costs [3].

Manufacturing process

Process analysis

In order to optimize processes, data collection is required. Data is obtained from the Enterprise Resource Planning software, quality and production records. Some information can only be obtained by observing (creating records or estimating parameters from related data) or creating a recording system.

A proposed methodology to optimize and implement new processes is DMAIC: define processes, measure parameters, analyze obtained data, improve current processes and control it.

Tools used by process engineering [4]:

- SIPOC analysis
- Process Flowchart
- Key parameters indicators and key performance objectives
- Graphical analysis
- Characterization of variables distribution

Nonconformance analysis

It is the responsibility of every OGMA's employee to report nonconformity detected at any stage of the process, in order to analyze and correct it, even when it involves products already delivered to Customer.

The product related functional areas (Production, Product Quality, Engineering, Planning, Programming & Control and Logistics) shall assess the nonconformity and decide on the action to be taken on the nonconforming product, involving in the decision, where applicable, the Customer, the manufacturer and the competent Aviation Authority.

Scratch-damaged Rear Pressure Bulkhead

According to the nonconformance product procedures, a nonconformance report delivered to the customer must be followed by substantiation (document that contains engineering analysis that supports the proposed solution).

One of the main causes of RAC openings at the rear fuselage is scratch damage produced during manufacturing. In order to understand how those anomalies affect the product life and the structural stability of the component a structural analysis is realized. This analysis is based on typical skin repairing procedures.

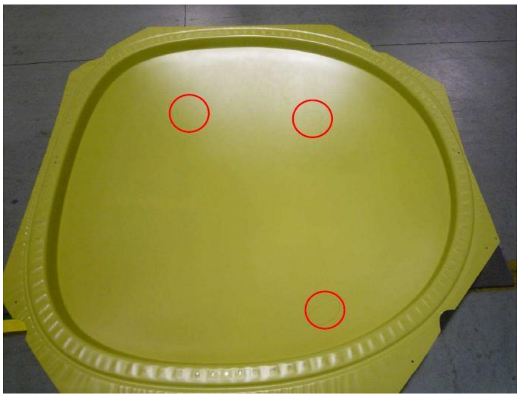


Fig. 3.– Example of typical anomalies found in a Pressure dome, 3 scratches on the inner face.

Fig. 4. – Scratch example. Courtesy of OGMA

Static Structural Analysis

The analysis is focused on finding stress distribution and loading of the rear pressure and the sensibility of this structure to a repairing operation, the skin thickness decrease. This analysis is based on commercial software, ANSYS APDL. Fuselage experiences a small percentage of lift loads, but the dominating load on the fuselage is the Inertia load. When the aircrafts fly over high altitude an internal pressurization is applied to create the sea level atmospheric pressure inside the fuselage cabin. This internal pressurization is considered to be one of the critical load cases in the design and development of the aircraft. A Pilatus PC-12 rear pressure bulkhead with all stiffening members is considered in this analysis.

The pressure rear bulkhead is connected to the airframe by a doubler that is connected simultaneously to a stiffener frame (frame36), rear fuselage and central fuselage skins and stringers. The frame is much more rigid than the pressure bulkhead flange, all tension loading at this section is supported by the frame. That is the reason why the selected loading for this analysis is a pressure load of 5.7 psi, which is the maximum pressurize differential of the Pilatus PC-12 NG.

<u>Geometric modelling</u>

A rear pressure bulkhead is considered for the analysis. The pressure rear bulkhead is manufactured from a solid formed sheet of aluminum of a constant thickness. The flange reinforcements and stiffeners are formed on the outer surface of the pressure rear bulkhead by chemical milling.

After getting the geometry of the pressure rear bulkhead some constraints are considered: symmetry of the component could simplify the analysis, working with a half and using the right boundary conditions, and a mapped mesh of quad elements would increase reliability of the model. Geometry complexity makes this mesh implementation difficult, manual area-by-area meshing was implemented in order to mesh as described. Even though, more complex areas are meshed using free-quad elements.

<u>Selected elements</u>

The selected element is Shell-181 for all component surfaces. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes.

SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. In the element domain, both full and reduced integration schemes are supported. SHELL181 accounts for follower (load stiffness) effects of distributed pressures.

<u>Boundary Conditions and Load</u>

All translation degrees of freedom of the RPB flange are fixed and rotation is free (supported flange). The load condition is the pressure load acting at the entire skin (from inner to outer surface).

Linear-static structural analysis

Applied boundary condition is a conservative approach to real boundary conditions, because stress at studied areas (flange and central membrane are not considered for this analysis) are over-estimated but in an acceptable range, and that means a safety factor greater than 1.5 for maximum pressure differential.

At flange, stress is under-estimated because the selected boundary condition (supported flange) reduces stress at flange and increase stress at the rest, comparing to real loading. Even though, it is a good boundary condition approach for this analysis.

At central membrane (the most stressed area), tension is over-estimated because of lack of stiffeners and as at the rest of the central area of the pressure rear bulkhead stress is sensibly over-estimated because of boundary conditions.

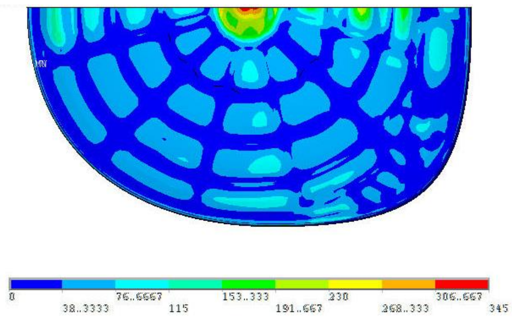


Fig. 5– Von Misses Equivalent Stress plot of outer face.

Thickness decrease sensibility analysis

With the purpose of understanding the impact of standard scratch repairing processes on pressure rear bulkheads. The selected defect is a scratch on the bottom center side of the pressure rear bulkhead, the standard repairing process is a progressive thickness decrease at the surrounding area. The modified area is $30cm^2$, and the modification is of 10% or 25% decrease of the nominal thickness. The selected mesh has 12846 shell-181 elements.

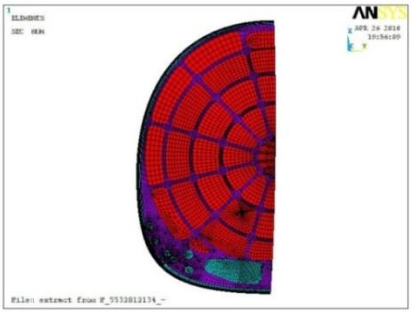


Fig. 6. – Thickness decrease analysis mesh, modified area identified in blue at the right picture.

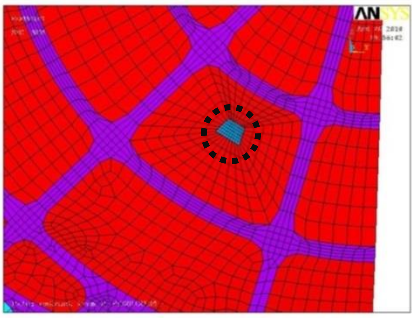


Fig. 7. – Detail of the defect.

The thickness decrease simulated generates a stress concentration at the surrounding area. The stress concentration generated at the FEM model is greater than in the real pressure rear bulkhead because of the smoother contour of the last, even though stress levels remain in the acceptable range and FEM analysis remains conservative.

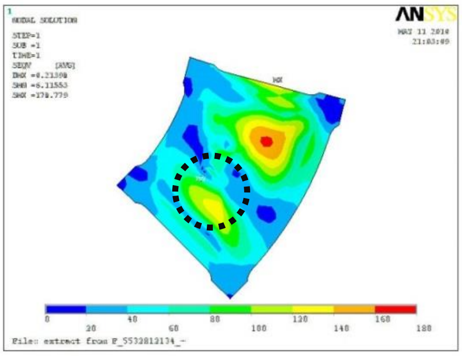


Fig. 8. – Von-Misses stress distribution for inner face thickness decrease of 25% at inner face, using refined mesh.

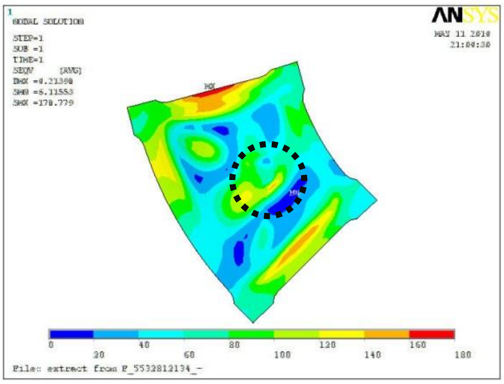


Fig. 9. – Von-Misses stress distribution for same thickness decrease at outer face.

The FEM simulation of pressure rear bulkhead with a repaired area on outer face with a thickness decrease of 10% presents a stress peak at the proximity of the defect. As result of inertia reduction of the section at this point, membrane stress is expected to increase as well as bending stress.

Stress concentration at edges

The maximum thickness reduction allowed during manufacturing is 10 %, and this is the reference to analyze criticality of the repairing operation. At inner face the effect on stress of the repairing operation is slight compared to stress concentration at milling edges, where stress value is almost the double of the value found at defect surroundings.

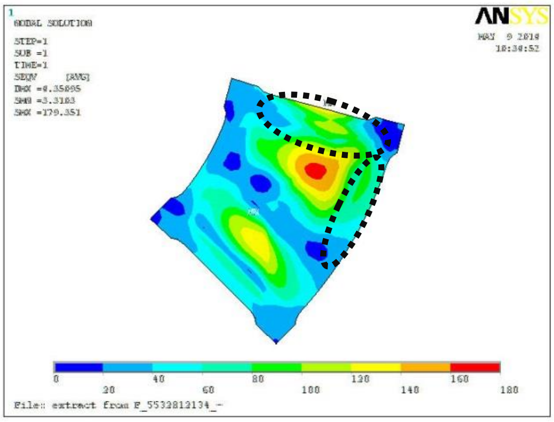


Fig.10. – Edges stress concentration at outer face thickness decrease of 10%, on outer face.

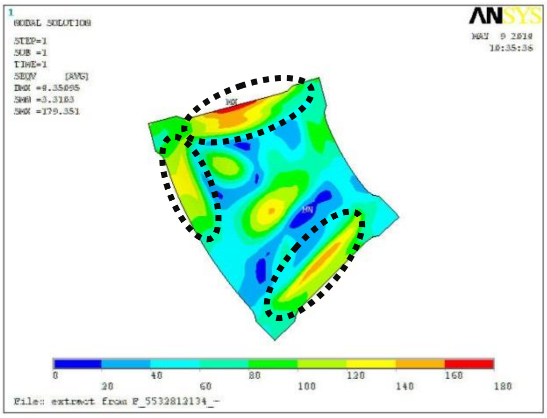


Fig. 11. – Edges stress concentration at outer face thickness decrease of 10%, on inner face.

At outer face, repair effect is slight as the edges effect on stress. To conclude, 10% of thickness reduction effect is almost negligible in front of the edges effect.

Lean methodology

Production optimization, from a first perspective, is the improvement of productivity in all processes involved in industrialization and manufacturing. Two methodologies were developed based on this principle: TPS and, later on, Lean manufacturing.

The Toyota Production System (TPS), originally called just-in-time production, is an integrated socio-technical system, developed by Toyota that comprises its management philosophy and practices. The Lean manufacturing is a management philosophy derived mostly from the Toyota Production System (TPS). The steady growth of Toyota, from a small company to the world's largest automaker has focused attention on how it has achieved this success, and bigger companies all around the world try to develop similar methodologies [5].

Lean is a production practice that considers the expenditure of resources for any goal other than the creation of value for the end customer to be wasteful, and thus a target for elimination. Value, from the Lean perspective, is defined as any action or process that a customer would be willing to pay for.

Both lean and TPS can be seen as a loosely connected set of potentially competing principles whose goal is cost

reduction by the elimination of waste. These principles include: Pull processing, Perfect first-time quality, Waste minimization, Continuous improvement, Flexibility, Building and maintaining a long term relationship with suppliers, Autonomation (Jidoka), Load leveling (Heijunka) and Production flow and Visual control.
Another way to optimize is automatize through numerically controlled (CNC) machine tool. While NC tools are controlled by a computer and can be programmed for several jobs, such as: milling, machining or drilling. NC tools are not flexible as robotic arms, but future factories will consist in a mixture of NC machines, conventional machines and robots.
Robotics provides reduction of direct labor, flexibility to redesign parts, 24-hour operation, performance on hazardous tasks, and a more uniform quality. Despite of the general cost-reduction oriented strategy, reasonable robotization could boost productivity in a mid-term horizon.

Gemcor G-86 implementation at PC-12 Assembly Line

Nowadays, state-of-art aircraft assembly lines use automated riveting process. That means that the riveting robot has the ability to cover the entire fuselage ton from the outside. Automated fastening proved in to be vastly superior in most of its implementations, in quality and speed, to manual or semi-automatic operations.
An assembly process is analyzed in order to automate it: right and left sidewalls skin riveting.
The high number of similar rivets makes sidewalls automatic riveting time-consuming and repetitive; these two characteristics make automation of this process a good way to increase productivity.
A computer-controlled flexible robot is selected for both components in order to reduce timeframes and quality variability. Extra investments are required to Gemcor G86's installation and its implementation at PC-12 line, further profitability research is required to justify its use for the Pilatus Aircraft Program at OGMA facilities.

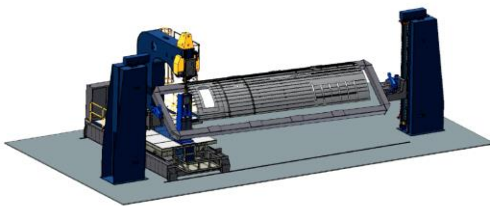


Fig. 12 – Component being riveted by an automatic fastening machine. *Courtesy of Gemcor*

Parametric analysis methodology

A parametric analysis is realized with the purpose of estimating savings of automation. Once the structures to assembly at this machine are selected, number and type of rivets must be defined. Due to the difficulty of defining a mean cycle time and predicting real machine costs, a study of the relationship between cycle time and machine costs is required.

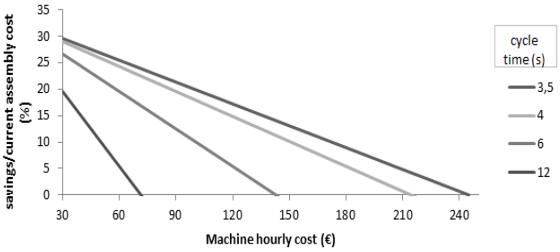


Fig. 13 – Profitability analysis of LH and RH PC-12 sidewalls riveting automation.

As it is expected to happen, the slower is the machine operation the smaller is the machine hourly cost range. Once the technological requirements and tolerances are defined, the appropriate machines could be selected and the machine hourly cost could be estimated.

Conclusions

Continuous improvement methodologies must be implemented in order to adapt current capacity and resources to demand, predicting bottle necks and reducing waste of resources. The proposed methodology for waste reduction is Lean, including Kaizen workshops implementation.
With these methods, Engineers can validate process data in a faster way, take decisions, improve systematically and, at the same time, operations becomes more reliable, which can ultimately lead to lower costs and improve productivity.

The RPB (rear pressure bulkhead) sensibility analysis enables to determine the static loads acting on the component and how defects affect its structural behavior, as well as understand effects of standard rework operations for this type of component. Even being a conservative approach, the component stress distribution is in an acceptable range and maximum admissible defects don't change significantly stress distribution. Through this analysis it is demonstrated that contours of milled areas have more affection on stress distribution than admissible defects. A more detailed validation would require the use of real testing and/or finite element method software using real boundary conditions and discussion of linear and non-linear analysis. The current trend of Aerospace manufacturing industry is to automate processes, new concepts of mobile jigs and all-in-one machines (riveting, countersinking, sealant applying). In order to analyze this trend and optimize the fuselage assembly process, automatic fastening machine implementation is analyzed for multi-program use. Sidewalls assembly automation increases productivity and quality and reduces timeframes and costs. However, requires further analysis of profitability and assembling related issues.

References

[1] Guia para la aplicación de la norma EN 9100 en industrias del sector aeronáutico. 1st ed. Sevilla: Instituto Andaluz de Tecnologia, 2003. ISBN 84-923464-8-5

[2] SABRe – Non-conformance Control, Rev. 18th: October 2007.

[3] Ricardo Anselmo de Castro- Lean Six Sigma: para qualquer negócio. 2nd ed. Lisboa: IST Press, 2012. ISBN 978-989-8481-21-4

[4] Kiyoshi Suzaki- Gestão no Chão da Fábrica Lean: sustentando a melhoría contínua todos os dias. 1st ed. Rio Meão: LeanOP, 2013. ISBN 978-989-20-4069-1

[5] Jeffrey k. Liker- Las claves del éxito de Toyota: 14 principios de gestión del fabricante más grande del mundo. 1st ed. Barcelona: Gestión 2000, 2010. ISBN 978-84-9875-074-4