The International TRIZ Conference ITC-2023

Fuel Saving Winglets - TRIZ Use Case

Prashant Yeshwant Smita Joglekar

prashantj@bmgindia.com

Breakthrough Management Group India (BMGI)

Abstract

One of the major cost drivers in an airline industry is Air Turbine Fuel (ATF). The volatile input constantly keeps its margins in check, even though fuel prices have slumped considerably, it has given airline industry nightmares all through its existence.

The case presented here was when everything was not going hunky--dory for the airline industry and aircraft manufacturers have to act on SOS basis with their innovations to curb fuel consumption. There were several ways explored to improve fuel efficiency.

The case discussed here considers the problem of vortex drag reduction at the wingtips which is one of the major contributors in reduction of the lift force, adversely affecting the fuel efficiency. Following discussion explores what the problem is, where it occurs, what are the contradictions to be addressed and how TRIZ (Systematic Innovation Science) contradiction matrix & inventive principles finds its application in the proposed solution which is tested and validated for improved fuel efficiency offering several other benefits. Author doesn't claim that TRIZ is used to arrive at the final solution, which is winglet in this case but wants to show application of TRIZ in already evolved design. This case is written with a view to generate interest of engineering professionals in TRIZ and encourage them to use it in technical problem solving in their own field of work.

The case shows broader & narrower problem definition to zero down on the key problem statements & contradictions. The paper discusses several type of drag forces acting on the wingtip that affects the lift force. The ideas & eventually the engineering solution that has come up achieved a vortex drag reduction to a large extent. Finally it lists several other benefits of winglets beyond saving precious Aviation Turbine Fuel

Keywords: *TRIZ, Drag Reduction, Fuel Efficiency*

1 Defining Broader & Narrower Problem

Every problem statement has a broader & narrower part to it. So, airline companies must have started with an original problem statement 'how to improve profitability' which is a universal problem statement across businesses irrespective of the type of industry. To zero down on the problem statement which we eventually want to work on, we use 'WHY-WHAT's STOPPING YOU TOOL' [1]. The tool asks us to keep the main problem statement at the centre and work upwards asking the question 'why do we want to solve this problem' to identify the broader problem statements. Similarly, the tool helps us go downwards by asking a question 'what's stopping us solve this problem' this will result in getting more granular problem statements that either business and / or its partners must work on to address the original problem which in this case was 'how to improve profitability of the airline'. (Figure 1)

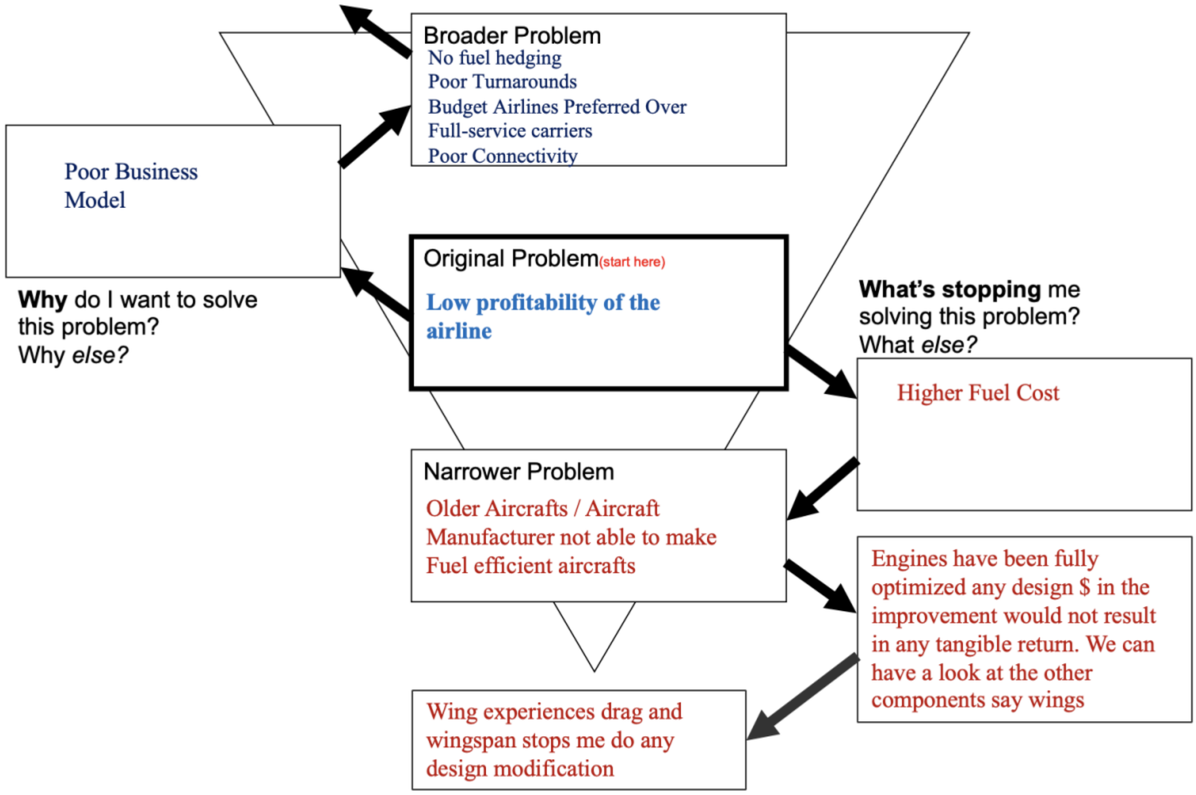

Figure 1: Why-What's Stopping Me Tool to Identify Broader and Narrower Problems

Whilst airline company's job is to work on the problems and associated factors that they have control on, which is mainly concerning their own operations & business model architecture. But when it comes to the problems that their partners need to address, they will have to take it up with them for resolution, which will benefit both airline company and aircraft manufacturers by delivering true value to their final customers, the travellers.

Our focus of discussion in this article is the narrower problem that aircraft manufacturer must define which is to improve fuel efficiency of the aircraft.

1.1 Narrower Problem

After the problem of 'making aircraft fuel efficient' landed on aircraft manufacturer's design room the first thing they must have done is to look at the system hierarchy of the product, aircraft in this case & decide where to put their efforts based on the benefit they expect to achieve as a result of their work, it may so happen that they will work on different aspects of aircraft sub-system which can potentially contribute to the improvement of 'fuel efficiency' (Figure 2) [1]

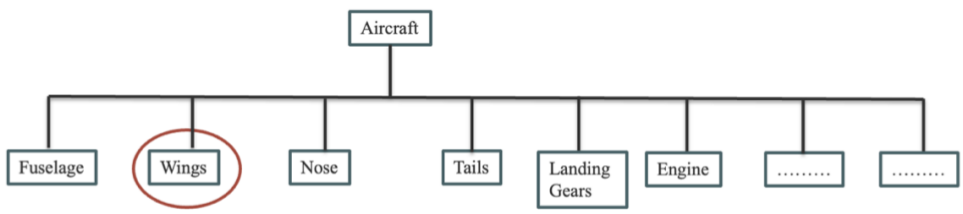

Figure 2: System Hierarchy Diagram to Shortlist Sub-System for Improvement

The engine looks to be an obvious choice as it powers the plane by consuming Air Turbine Fuel. But any investment in already optimised engine may not give manufacturer significant improvement in the fuel efficiency. There are other components to be looked at which may require minimum investment to improve and are a good candidates for fuel efficiency improvement.

Wing was chosen as a probable candidate for possible redesign for improving fuel efficiency. Let's dive into detail to look at the problems with the wing structure, air dynamics around the wing that contributes to the lower fuel efficiency.

1.2 Airfoil Components & Lift

An air foil is the shape of a wing. Subsonic flight have a characteristic shape with a rounded leading edge, followed by a sharp trailing edge, often with asymmetric camber. (Figure 3) [2]

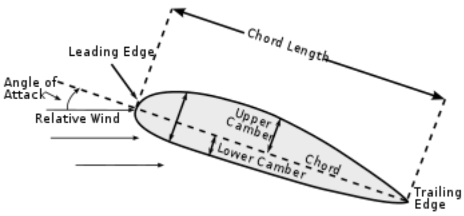

Figure 3 : Air Foil Geometry (Side View)

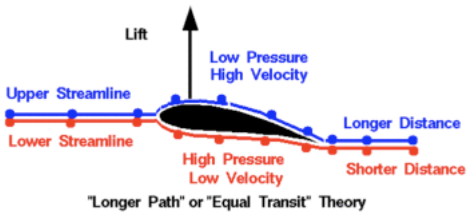

Figure 4 : Air Flow Around The Air Foil

If we recollect Bernoulli's theorem which says the total pressure of an incompressible fluid is the sum of the static pressure & the dynamic pressure. If the fluid is air and the means by which the fluid is accelerated is an air foil, the side on which the fluid travels the maximum distance will have the highest velocity and lowest static pressure and vice a versa. The difference in the velocity on each side of the air foil determines the static pressure differential. That is what generates lift. The lift on an air foil is primarily the result of its shape and its angle of attack. When either or both are positive the resulting flow field about the air foil has a higher average velocity on the upper surface than on the lower surface. The velocity difference is necessarily accompanied by a pressure difference, which in turn produces the lift force.(Figure 4) [3]

Designing a wing would have been simple if it were a two dimensional air foil. But wing has a finite length. The difference in air pressure between the lower & upper surfaces of a wing causes the air to escape around the wingtip which reduces the available lift. We will see the phenomenon in detail in the following discussion on drag.

1.3 Drag

Drag simply means the harmful forces acting on the wing which reduces the available lift. There are two types of drag the first type is lift induced drag which is 40% of total drag and the other is parasitic drag which is around 60% of total drag.

1.3.1 Lift & Induced Drag

The lift induced drag is a drag which occurs as the result of the creation of lift on a three dimensional lifting body. Induced drag primary consists of two component the vortex drag and the viscous drag.

The motion of the air rushing around the wingtip coupled with the velocity of the airflow through which the wing is flying causes a vortex to be formed near the wingtip (Figure 5) [4].

The tip vortices cause upwash and downwash air currents that alter the current of the free stream flow around the wing. They induce a decrease in the angle of attack of the average relative wind flowing around the wing. This has two undesirable by-products as shown in figure below. First the wing generates lift perpendicular to the average relative wind. This diverts the lift vector away from the desired direction which is perpendicular to the free stream. Diverting the lift vector causes a drag component to be generated that is parallel to the free stream airflow. The drag component varies as the cosine of the angle between total lift vectors (Figure 6)

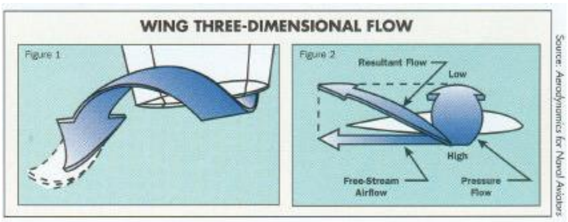

Figure 5 : Wing Three Dimensional Flow

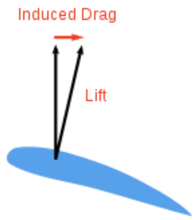

Figure 6 : Induced Drag & Lift Vectors

The up-wash / downwash effect (Figure 7) [5] of the tip vortices (Figure 8) [6] has its greatest influence of the wing section closest to the tip. The tip vortex has little effect on the average relative wind of the wing sections far inboard from the wingtip. In other words, if you push the winglets outboard, a smaller section of the wing will be effected by the tip vortices which will reduce the upwash and downwash effect. In other words if the span were infinite induced drag would be zero because there would be no wingtip.

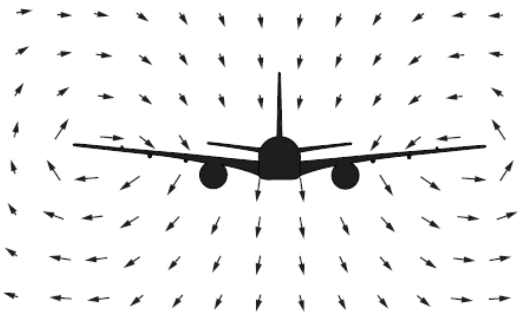

Figure 7 : Upwash / Downwash Effect

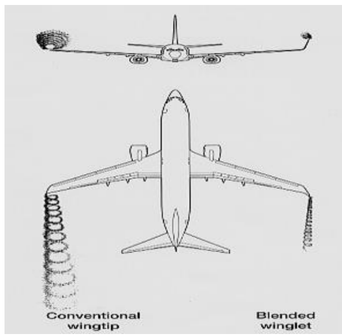

Figure 8 : Vortex at the Wingtip

1.3.2 Parasitic Drag

Parasitic drag is drag caused by moving a solid object through fluid. This is around 60% of the drag. Parasitic drag is made up of multiple components including form drag which is a result of form of the object, skin drag which occurs because of interaction between the skins of the object. As seen above a very large long wing, one with infinite span to chord ratio would have enormous parasitic drag. But with optimised wing span, chord and air foil sections the drag can be controlled. However still the vortex drag remains & affects the wingtip reducing the overall lift.

1.3.3 No further optimisation possible as system hits the fundamental limit

The vortex drag can be theoretically minimised by having an infinite span to chord ratio known as aspect ratio. Now if we optimise the aspect ratio for the improvement in lift coefficient then the result shows us that there is a marginal difference in the lift coefficient for the aspect ratio (Figure 9) [7] starting from 8 onwards to infinity, which means the system has hit the fundamental limit and cannot be improved by further optimisation (Figure 10) [8]

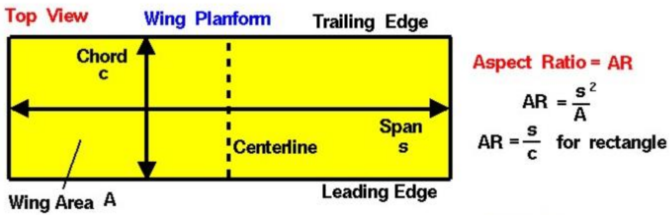

Figure 9 : Wing Geometry & Aspect Ratio

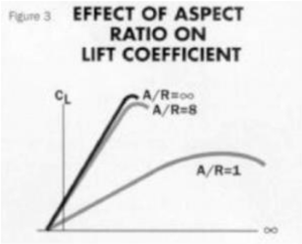

Figure 10 : Aspect Ratio & Lift Coefficient

2 TRIZ Contradictions Matrix & Applicable Inventive Principles

2.1 Contradiction Formulation

As evident from the above discussion, wingtips create a drag by the vortices it generates. This drag causes more fuel burn increasing the operational cost for airline companies. Drag can be reduced by increasing the wing-span. We can use optimisation tools to optimise aspect ratio (span to area ratio) to get the best results for lift coefficient. But there is a cost to an experimentation and beyond a point it may not be feasible to do optimisation.

Now if wing span is increased according to our wish for maximising lift coefficient, the plane may not fit the gate after landing it on the ground. At present in 747 aircraft wings are attached to fuselage nearly by 1600 bolts any increase in length will weaken the strength of this ‘fuselage & wing joint’ it will also hamper manufacturing cycle time. So increasing wing length is not easy as it looks [9]

Now on formulating contradictions for this problem. Some of the TRIZ researchers are of the opinion that physical contradiction is more important than a technical contradiction. While some other TRIZ researchers believe that both/and approach of contradiction resolution is far better than either/or approach. [10] The discussion here shares a new approach of conversion between Physical & Technical Contradiction using theory of constraints tool ‘Evaporating Clouds’ [10]

The approach goes something like this on the right hand side of the figure 11 there are two ovals ‘Parameter A’ and ‘Parameter -A’. These two, exactly as defined by evaporating cloud model, represent physical contradiction. The ‘Conflict Parameter 1’ and ‘Conflict Parameter 2’ ovals then represent our technical conflict pair. Although these two items are also in the original Evaporating model, they are not identified as being in conflict with each other. We may make this connection more explicit in the figure 11 by connecting two ovals. This represents our technical contradiction since the way in which we define the problem, we want to have two contradicting defined parameters. Finally on the left hand side of the picture is the oval labelled ‘successful outcome’ this is the aspect of our system that both the conflict parameters are required to support.

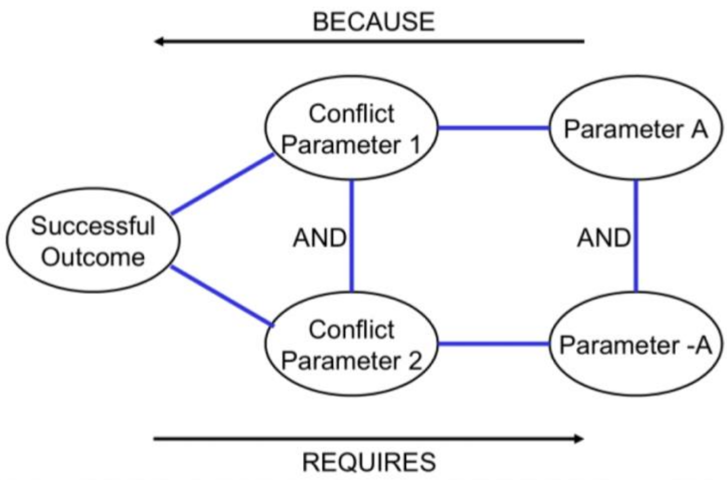

Figure 11 : Generic Scheme of Converting Between Physical & Technical Contradictions

We have applied this framework to our vortex reduction problem and the resultant scheme representing relationship between physical & technical contradiction is as under (Figure 12). The goal of this contradiction resolution framework is to find innovative ideas inspired by TRIZ inventive principles to lower vortex force without increasing the length or span.

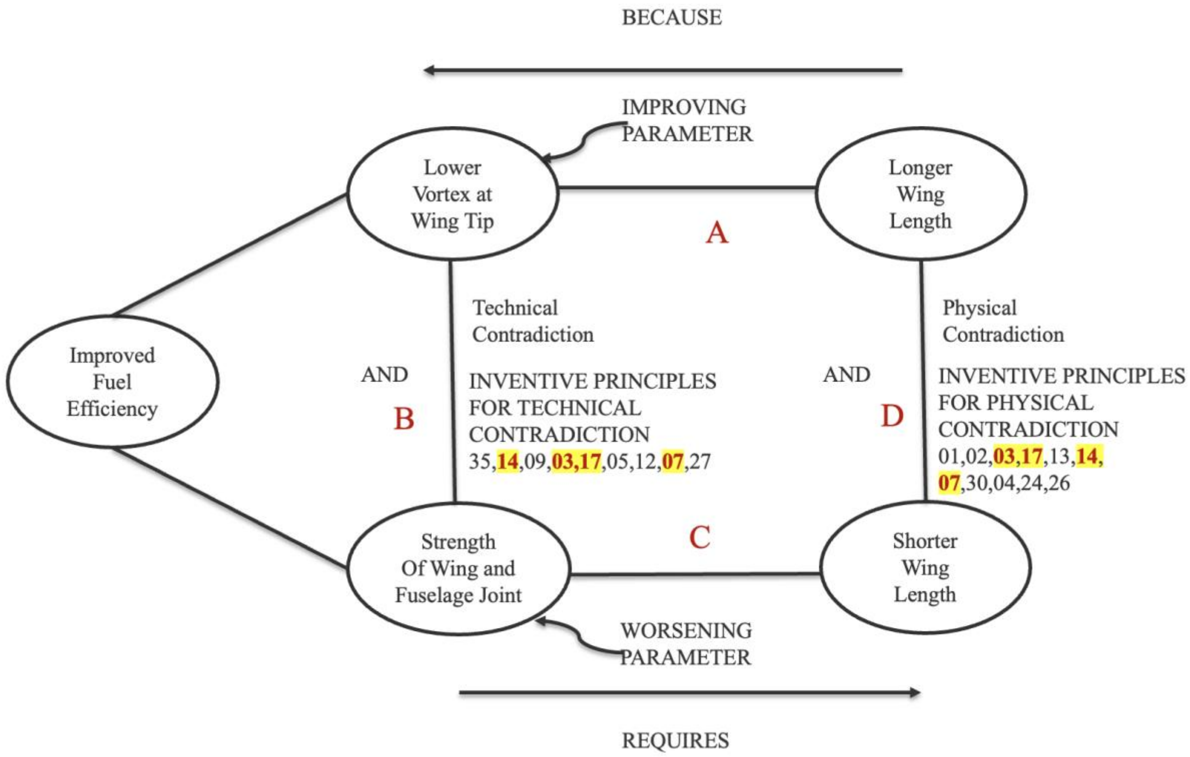

Figure 12 : Physical & Technical Contradictions Connection to VORTEX Reduction Problem

Let us discuss this framework in detail. Let's start with connection A (Figure 12). Now tip vortex reduction is our main goal. Following the concept of Ideality (Ideal Final Result) the true value of this attribute should be zero at least theoretically which is possible if we have infinite wing length. This is how we make this connection A. The lower vortex drag (ideal value zero) results in no loss in lift force which results in less fuel burn. The outcome of this solution is improved fuel efficiency.

Wing is connected to fuselage by 1600 bolts, now when we increase the length of the wing many folds as mentioned in connection A, obviously the existing strength of the joint will pose a challenge and will be a worsening parameter, which necessitates us to have a shorter wing length. Refer Connection C of Figure 12.

2.2 Contradiction Matrix and Applicable Inventive Principles

Thus, now we have a technical contradiction represented by connection B where improving parameter is vortex force (TRIZ Contradiction Matrix Technical Parameter #15 Force) and worsening parameter, the parameter that stops us from achieving this (TRIZ Contradiction Matrix Technical Parameter #20 Strength)

The inventive principles applicable to resolve such type of contradiction are represented on connection B they are 35 – Parameter Changes, 14 – Curvature, 09 – Preliminary Anti-Action, 03 – Local Quality, 17 – Another Dimension, 05- Merging, 12-Equipotentiality, 07- Nested Doll, 27 – Cheap Short Living Object [10]

Now let’s examine connection D which represents a physical contradiction with attribute as length. The physical contradiction in space here is ‘Longer Wing Length’ and ‘Shorter Wing Length’, where we want two opposite properties in the same object.

The brilliance of TRIZ, 70+ years old researched innovation science is that it leads innovation teams to an ingenious solution to the problem, that at first, looks difficult or crazy enough to solve.

The inventive principles suggested to solve this type of physical contradictions are. [1]

01-Segmentation, 02- Taking Out, 03- Local Quality, 17- Another Dimension, 13- The Other Way Round, 14- Curvature, 07- Nested Doll, 30- Flexible Shells and Thin Films, 04- Asymmetry, 24- Intermediary, 26- Copying

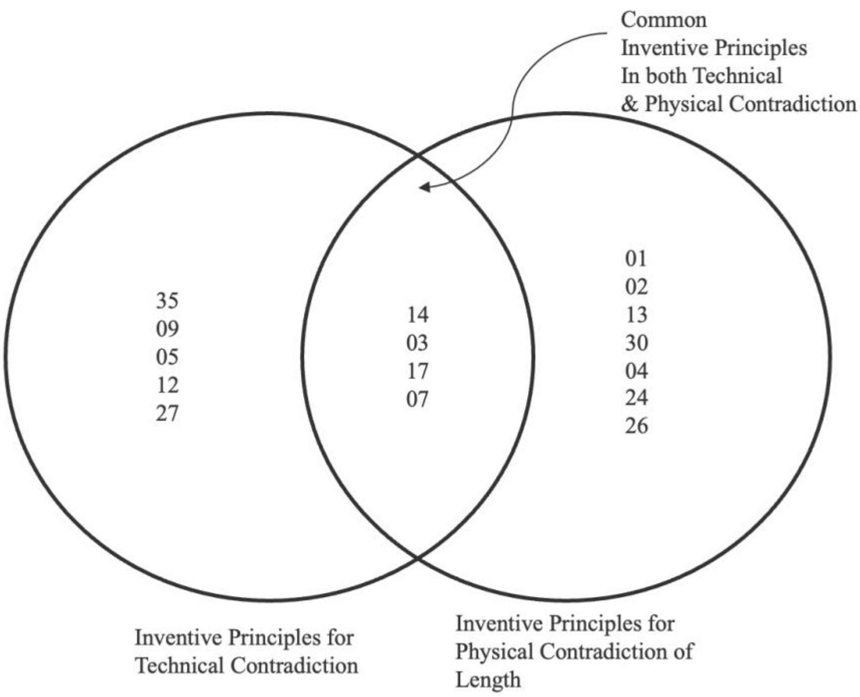

Figure 13 : Common Inventive Principles in Both Technical & Physical Contradiction

2.3 Inventive Principles Application & Solution

Aircraft engineers would have made us believe that aerodynamics is a mature science until NASA’s Richard T Whitcomb invented vertical winglets which could reduce the drag by nearly 20%. As we have seen above that stretching wingspan or increasing aspect ratio certainly reduces induced drag. But designers though must balance the benefits of less induced drag against the cost of structural weight increases, more parasitic drag, or cost considerations.

Winglet works because they efficiently produce side forces that divert the inflow of air from tip vortex & therefore the drag, so lift is not affected as it is with the normal wing and there is an improvement in lift to drag performance resulting in lesser fuel consumption.

Here is decoding Inventive Principles with their interpretation. We chose 9 out 20 which appear more appropriate for ideation or already have solutions that is contributing to vortex force reduction. (Table 1)

Another insight from the above method we got is the commonality of inventive principles suggested for technical & physical contradictions. So, inventive principles 14,03,17,07 find application in all winglet design options. So, this type of contradiction formulation offers reduction in ideation time and faster implementation of solutions.

Table 1: Inventive Principles and Interpretation of Most Relevant Principles

Inventive Principles	Interpretation of Relevant Inventive Principles
14 Curvature	Turn straight edges or flat surfaces into curves
03 Local Quality	Change things around the system from uniform to non-uniform. Enable each part of a system to function in locally optimised conditions. Enable each part of a system or object to carry out different useful functions.
17 Another Dimension	If system contains or moves in a plane, consider use of dimensions or movement outside the current plane
07 Nested Doll	Put one object & system inside the other
35 Parameter Changes	Change the pressure, change the concentration & consistency. Change in parameter has to be a step change and not intended to be an optimisation strategy
05 Merging	Physically join or merge identical or related objects, operations & functions
27 Cheap Short Living Object	Replace an expensive object or system with a multitude of inexpensive short living objects
04 Asymmetry	Where an object, process or system is symmetrical or contains lines of symmetry, introduce asymmetries
02 Taking Out	Temporally separate different elements of an object or system

We see application of these inventive principles in various winglet design that are in existence to reduce the vortex force and improve fuel efficiency. [11]

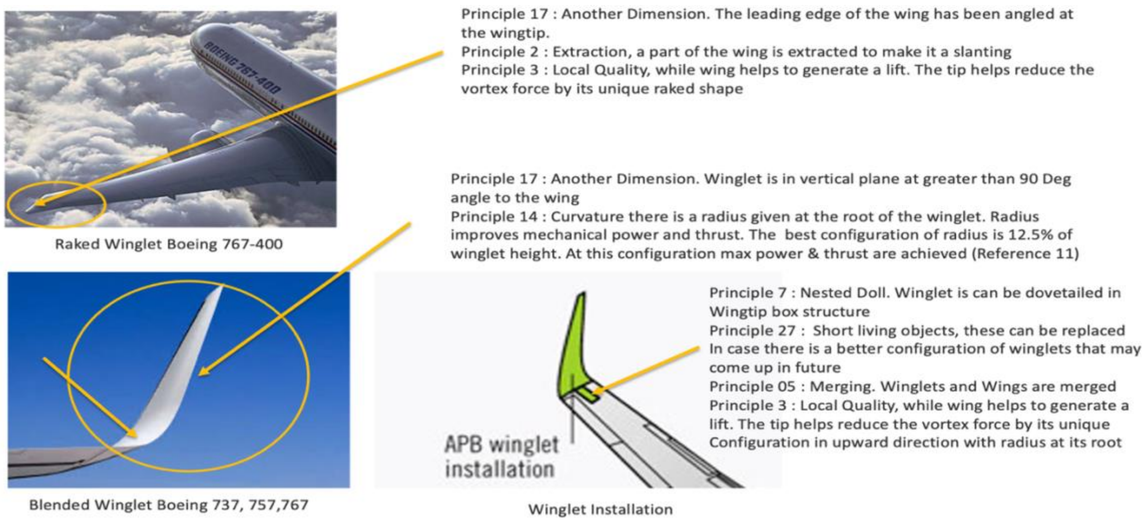

Figure 14: Winglet Designs and Applicability of Inventive Principles

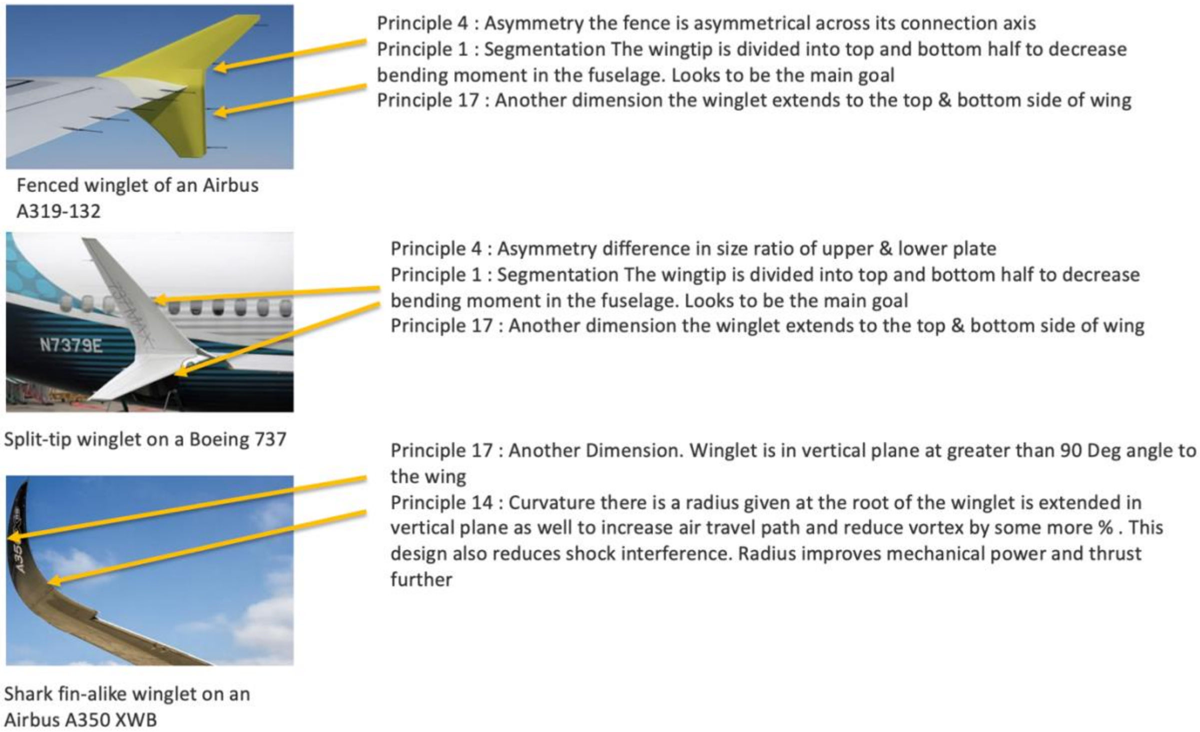

Figure 14: Winglet Designs and Applicability of Inventive Principles

Benefits of Introducing Winglets

a) Fuel consumption reduced over 7 % at speeds between 0.75 Mach to 0.80 Mach

b) Typical 737 operators save @ 95,000 – 1,30,000 gallons per aircraft per year and this is for the entire economic life of the aircraft

c) It has also environment benefits which reduces carbon monoxide and nitrous oxide by 4 % & 5 % respectively

d) Increase in the flight speed, improved stability & also faster climb to initial cruise altitude

e) Reduction in the take-off distance also benefits the airline operator to use airports having the shorter runways.

f) The increased lift offered by the sharklets also provides a larger amount of cargo to be loaded.

2.4 Conclusions

TRIZ is a wonderful innovation science. Several of its problem formulation and solution generation tools have been validated by extensive research conducted over past 70 years and being continued today to help present-day every changing business & technology landscape.

"Someone somewhere has solved a problem "is the basic premise of TRIZ. The case discussed here shows how to formulate correct contradictions and how we can use tools from other world class approaches like TOC to help us generate innovative solutions.

It is my experience that if organisations use TRIZ for problem definition and ideation, they will get breakthrough ideas which will help them stay ahead of their competition. The process should work best when you have TRIZ facilitator & subject matter experts working as one team.

One of the ways teams can learn TRIZ with reverse ideation that is by looking at the solution which is already there then thinking on the contradictions that it has overcome.

If 20th Century was of experts creating SILOS, then 21st century is of Innovation Generalist who will use systematic Innovation Process & Toolkit to connect the domain experts to create ingenious innovative solutions that are well & truly IDEAL or at least close to ideal.

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