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Design for Six Sigma, its Potential Effect on Weight in Modern Military Aircraft

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ABSTRACT

Six Sigma is one of the current quality tools that is being introduced in to the design and manufacture of products. The paper starts by introducing the reader to Design for Six Sigma (DFSS), on which the concept is based and the key stages within the DFSS process. The goal of DFSS is to reduce the amount of variation in the design so that fewer defects are seen in manufacturing. To reduce variation and defects in a product the designed tolerance and the manufacturing process capability need to be increased. However, there is little current published research on the effect that this would have on the overall assembled product and the customer requirements in modern military aircraft. One of the most crucial customer requirements within the military aircraft industry is that of weight. This research identifies the potential risk associated with meeting the customer requirements if variation reduction is implemented into the design. The findings in this research indicate that there could be potential issues, including excessive costs to the long term customer requirements.

Keywords; Design for Six Sigma, Design for Manufactured, Aircraft Design

1 Introduction

Six Sigma was first introduced by Motorola, Pyzdek (2003), in the mid 1980's where Bob Galvin, Motorola's CEO at the time, started the company on the quality path known as Six Sigma and became a business icon largely as a result of what he achieved in quality at Motorola. Using Six Sigma Motorola became known as a quality leader and a profit leader. In 1988 this secret became public knowledge and the Six Sigma philosophy became a new quality initiative. Even though Motorola has been struggling during the past few years, companies such as GE and AlliedSignal have taken up the Six Sigma banner and used it to lead themselves into new levels in their customer markets. Indeed, it lies at the heart of local firm DB Textrons process improvement programme.

The six sigma process is used for achieving a robust design, using a variety of quality techniques. Hoehn (1995) breaks the process into six distinct stages, each step capturing various data through the design process helping to achieve robust designs and enabling manufacturing to produce cost effective products;

1. Defining the Requirements; this stage establishes the customer requirements which can be both physical and functional.
2. Identification of the key characteristics; these are specific features within the product that will effect the end result. In this step an analysis is required to identify these critical areas and how they will effect the customer's functional requirements.
3. Once these features have been identified it needs to be established as to whether each characteristic is controlled by parts, process or a combination of both.
4. The selection of the key features identify which areas need to be looked at in more detail to establish targets and tolerances, this may require breaking down each process into more detail.
5. The variations in the key features are looked at and identified using various tools; statistical process control, design of experiments etc.
6. This stage combines the information gathered above to implement continuous improvement into the product and design.

2. Design for Six sigma

The aim of Design for Six Sigma (DFSS) is to reduce the amount of defects that the designed products may contain in manufacture, hence the reduction of variation in the product. This variation may be derived using various quality measures including Cp, Cpk, (these are process capability measures that look at the process variation, C = capability, p = process and *k* = *katayori* Japanese for deviation or offset) defects per unit (DPU), defects per million opportunities (DPMO) and sigma value. A defect is where a manufactured product is outside its specified designed limits, making the product unable to meet its functional requirements. Hoehn (1995) classifies defects in four areas;

1. Defects that are attributable to the manufacturing process itself.
2. Defects that occur in manufacturing, but are attributable to product design.
3. Defects that occur at an integration level, but would not have occurred if adequate tests had been performed at lower levels.
4. Defects that result in the product not fulfilling its requirements.

DFSS's objective is to remove the sensitivity in the design process prior to the start of manufacturing. Efforts in the reduction of this should be focused on design / process decisions that have an impact on the customer's requirements; these are sometimes referred to as key characteristics. With this focus on the reduction of sensitivity to produce a robust design, Hoehn (1995) identifies three areas in which this can be achieved.

1. If the design has insensitivities but the process has a high degree of variability, then efforts should be focused on refining or changing the manufacturing process to minimize process variability.
2. If the design is highly sensitive but the process has low variability, then efforts should be focused on redesigning the product.
3. If the product has a degree of sensitivity and the process has a high degree of variability, then both the product and process must be corrected.

The term sigma refers to a standard deviation; this takes all the variation into account and is the measurement of variation around the mean. The calculation for this is:

$$\sigma = \sqrt{\frac{\sum (xi - \bar{x})^2}{n-1}}$$

xi = Each number in the data sample
$\bar{X}$ = Mean
n = Number of values in the data sample

Figure 1 illustrates six sigma with a "bell curve" where the majority of the variation is around the mean with smaller amounts of variation moving out plus or minus from the mean.

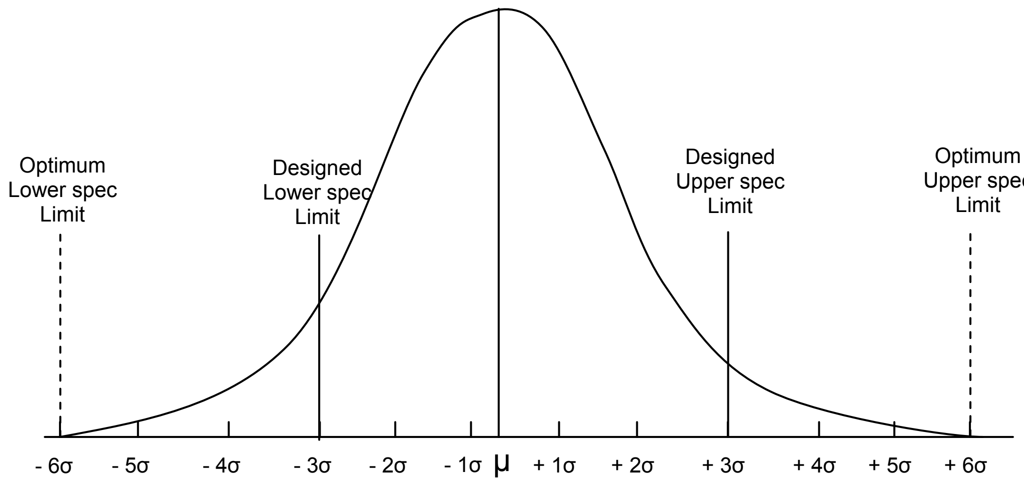


Figure 1 – Normal Distribution, 3 sigma design, 6 sigma optimum design

If the designed specification is within 3 sigma then, traditionally the amount of variation would have been acceptable within manufacturing of the product. However due to the introduction of DFSS, these traditional amounts of variation have been challenged to produce a 6 sigma variation. The benefits of these can be seen more clearly with the introduction of DPMO, defined by Motorola, Harry (1997), where they translated the sigma level into the number of defect parts per million parts manufactured. The figures below highlight the connection between the sigma level, % variation and DPMO.

Sigma level	**% Variation**	**DPMO, short term**	**DPMO, long term**
+/- 1σ	68.26	317,400	697,700
+/- 2σ	95.46	45,400	308,733
+/- 3σ	99.73	2,700	66,803
+/- 4σ	99.9937	63	6,200
+/- 5σ	99.999943	0.57	233
+/- 6σ	99.999998	0.002	3.4

These figures show 2 DPMO relationships; short term and long term. It is best to explain this by use of an example of a component being manufactured on a lathe. Over time the cutting tool would wear, this will cause the disruption of the performance variation to shift, while the designed specification limits remain the same. This shift was observed by Motorola and other companies that adopted this process. It was estimated that the shift would be around 1.5σ, and was used to define long sigma as opposed to short sigma.

The benefits between the design specification and the optimum specification can be clearly seen, a simple practical example can highlight this. If three components were housed in an assembly fixture, figure 2, the middle component 'A' needs to be positioned during the assembly process between components 'B' and 'C'. If the component variation has a designed specification of 3σ, then component 'A' would fit 99.73% of the time or for every million installations it would have an interference fit 66,803 times. However, if the components variation was increased to the optimum design specification 6σ then component 'A' would fit 99.999998% of the time and out of one million installations it would not fit 3.4 times.

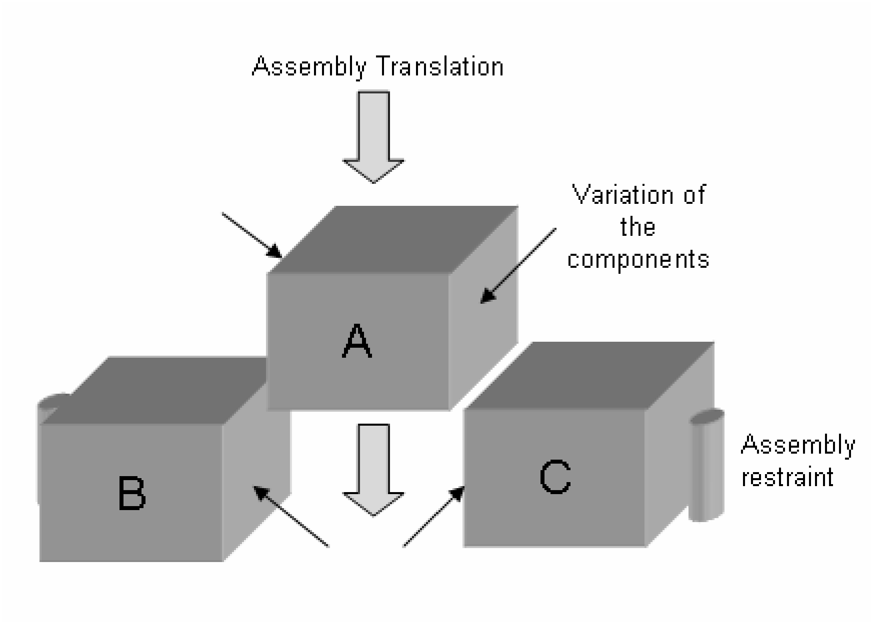


Figure 2 – Simple assembly example

3. Aircraft Weight

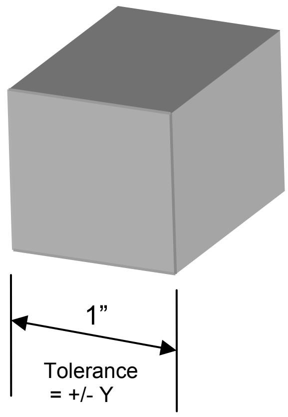
There are additional complexities when designing modern military aircraft, over other industries that design less complex products. One of the major requirements the customer has in aircraft design and manufacture is that of mass. Weber (1994), states that aircraft are weight critical; every pound of unnecessary aircraft structure weight reduces aircraft performance, aircraft payload, or the distance the aircraft can fly without refueling. Every pound of aircraft weight requires fuel to fly it for the life cycle of the aircraft. Fighter aircraft structures are designed for a life of 6,000 + flying hours. This translates into a fuel cost of approximately $50,000 (assuming an oil price from when the research was undertaken) per pound of aircraft weight over the life of the aircraft.

4. The Effect DFSS has on Aircraft Weight

As discussed the DFSS theory implements cost savings into the design by controlling the amount of variation in the product. To do this the design tolerances have to be increased along with the process capability in manufacturing. Due to customer demands in designing and manufacturing modern military fighter aircraft the airframe needs to be produced to much higher tolerances than previously seen in legacy aircraft, therefore it adds additional pressure to achieve good process capability results. With this in mind, if the demands of DFSS are to be achieved, the majority of variation reduction will have to be addressed by increasing the designed tolerances. With DFSS introducing the theory of controlling the design using quality tools and implementing them, industrialists are beginning to question the impact to the overall life cycle and in particular its impact on the key customer drivers. As there is no published research within this area, a study to review this area has been initiated.

Current aircraft are complex products with a large number of components that are required to produce the aircraft to the customer requirements. Modern military aircraft use light weight materials in their airframe and can be built from about 50% composite materials, with substantial use of titanium and lithium-aluminum alloys. Due to this many of today's aircraft are substantially lighter than their predecessors. Advanced construction techniques have reduced the major parts count of the airframe, to typically 16,000 structural elements.

Figure 3 highlights the effect in increasing the design tolerances on aircraft by using a simple example. It assumes that to reduce the variation in a product of 3 sigma to 6 sigma, the design tolerance would have to double e.g. +/- 0.007" would increase to +/- 0.014". The effect on the mass on a block of material 1" cubed of various material types is highlighted in figure 3.



If Y x 2, the weight would increase:

Aluminium > 0.13%
Titanium > 0.32%
None Metallic > 0.04%

Figure 3 – Weight of a solid compared to variation of the tolerance

If we translate these percentages material and weight types the increase in weight can be calculated

Material	None Metallic	Aluminium	Titanium
Weight (lbs)	12122.5	9213.1	2909.4
Additional Weight (lbs)	4.8	12	9.3

This would introduce a further weight increase to the aircraft of 26.17 lbs. Using Weber (1994) factors of $50,000 for every pound of extra weight due to fuel costs, over the life of the aircraft this would equate to approximately $1,306,800 or approximately £726,000 per aircraft.

This worse case assumption can be multiplied across a fleet of aircraft which governments may sustain. Comparing this to Weber (1994) these potentially hidden costs to the customer could be extremely significant. However, these figures are an approximation in the worst case; it would be extremely unlikely that each part would be produced on its maximum weight; however these costs are so extreme that a small amount of weight would carry a significant cost to the customer as the following chart highlights.

Percentage of increase in variation	Increase the cost of the fleet of aircraft
100 %	£168,432,708
50%	£84,216,354
25%	£42,108,177
10%	£16,843,270
5%	£8,421,635
1%	£1,684,327

4 CONCLUSIONS

The effect of the increase of tolerances, to reduce product defects in manufacturing is a key theory in DFSS. These increases have been applied to a modern military fighter aircraft. The material selection has been identified and with the increases in tolerance the mass has been calculated. The results from this indicate that there would be a significant cost to the customer due to the increase in weight. The calculations that have been used are from the worse case, where the products have been produced on their maximum tolerance. Clearly the likelihood of these occurring is slim, however the potential cost effects to the customer are so significant that if the components here manufactured and only 1% of the increased design tolerance was used then the cost to the customer would be £1,684,327 for the production of the aircraft. This highlights that when designing aircraft or any product the effect that the design has on the main customer requirements needs to be considered and design teams should not isolate themselves to the immediate issues as their effect on the complete product could out way the issue. Further research is ongoing to identify a novel process to measure the robustness of a design in the aircraft industry prior to manufacturing commencing

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