# REDUCING THE IMPACT OF TEST BENCH COMPONENT ON THE THRUST MARGIN MEASUREMENT

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**Abstract**: Turbofan main performance characteristics is its thrust. The engine is sold for a given thrust and cannot be deliver under a minimum threshold. Hence it is fundamental to evaluate thrust with precision. However, reception tests when all engine functions are verified before delivering to each airline company are realized in different bench test cells, under different weather conditions, with different pilots, and so on. All those context variations implies that the measurement is far to be normalized. Moreover, the certification process propose computation of a marginal thrust $(M)$ which is the relative difference between standard thrust $(\bar{T})$ and a specified value $(T_0)$: $M = (\bar{T} - T_0)/T_0$. The standard thrust is obtained from the measurement in the bench test reported to normal standard ISO conditions. This is computed for each rating proposed for each type of engine. The ratings correspond to the ability to power a given aircraft but in this first study we only consider the most restrictive rating.

Even after releasing the acquisition context constraints we still observe that the thrust margin is widely dispersed due to the test conditions. The dispersion of the thrust margin results from the complexity of the test conditions such as: complementary technical adaptations (ATC), benches and sites. Thus, it has been found that the measurement of the thrust margin is particularly influenced by certain important components such as secondary nacelle and the bench itself.

One of our objectives is to make the thrust margin independent of the test conditions and to reduce its dispersion. This task is complicated by the fact that engine parts comes from different providers and we also try to follow the production trends of each part supplier independently.

The resolution technique consists of two steps. During the first step we describe the evolution of the thrust margin independently of the absolute level resulting from one or more components of the bench, we proceed as follows: we associate each measure of thrust margin to a stable period where the test conditions are constants. A mean value is attributed to each stable period. Then we identify the gap between the evolution of the measured thrust margin and the mean value independent from the measure conditions. Once the average model evolution of the margin of thrust is set up. The second step is to identify the average bias introduced by each component of the bench.

Concretely, the application of this method has made it possible to reduce by about a factor of 2 the dispersion of the thrust margin, hence achieving a gain in accuracy of the measure by 50% and allowing us to ensure a continuous and accurate monitoring of the calibration of the benches and components based on operational measures, characterize the trends quality of the FAN blades provided by the suppliers, make measures of thrust margin more robust against the evolutions of the test conditions.

**Key words**: Turbofan Engine Performance; Thrust; Normalization; Bench Test Cells; Fabrication Process.

**Introduction**: Turbofan components are produced by several suppliers each using their own different fabrication processes. It is natural to find variations between performances of engines, but with different sources of fabrication this variation is not only the result of process uncertainties but also of trends generated by each different production schemes. Furthermore, the reception tests that verifies all engine functions before delivering to an airline company is done in different bench test cells, under different weather conditions, etc. So the performance trends are really perturbed and difficult to explain. As we will see below, they essentially depend on tests benches, tests bench components like cowls, sites and suppliers. Moreover there is still missing data to explain the acquisition context and the bench test measurements should be confirmed and normalized. (Here are some references about our previous work on bench test cells and normalization algorithms [1]–[4]).

The goal of thrust margin modeling is to normalize the measurement against the effect of these heterogeneous conditions:

- So, for each supplier, we describe thrust margin evolution independently of the absolute level generated by the cowl and test bench.
- For all measures, identify the bias introduced by test bench component.
- Identify thrust margin normalized gap between all suppliers.

The study is about the thrust margin of the turbofan engine and the main component responsible for the thrust on such engine is the fan, but our approach is essentially databased and does not use any physical model. Such models are mainly used to control the thrust online [5], [6]. Our study is about the production and design optimization, moreover we restrict out analysis to the supplier of fan blades. In this work we present only the impact of the supplier production on the thrust measurement which is mandatory to understand and computes the bias of benches and other equipments. In another study not presented here we were able to complete the work by anticipating the margin value using only the fan blades geometric measurements.

**Description of the observations**: Our measurement of interest during the reception test is the thrust margin (the percentage of thrust residual above a bottom limit). Higher is this margin, better is the engine. As observed in the Figure 1, a gap between thrust margins exists between each couple of suppliers. This is confirmed by the thrust margin distribution Figure 2 and thrust margin mean comparison between suppliers (Figure 3).

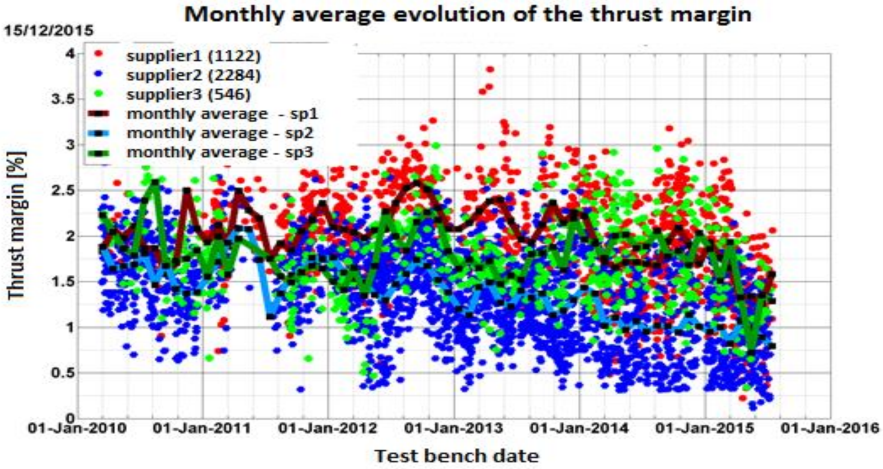

Figure 1: Observation of the thrust margin measured on each engine during the reception tests. Plain curves shows monthly smoothing. The different colors correspond to different supplier. We clearly observe difference of the production thrust mean between suppliers.

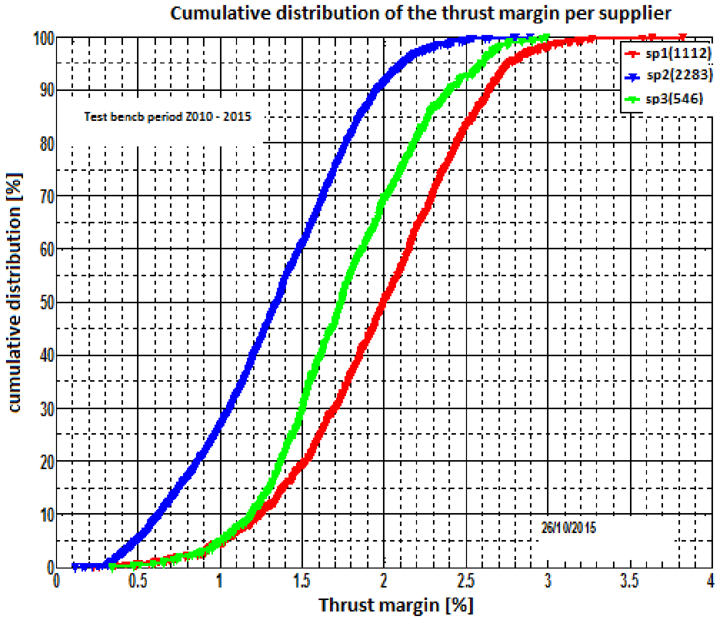

Figure 2: Repartition functions for the thrust margin by supplier. The abscissa represent the thrust margin which is the percentage of residual thrust over a bottom limit. The 50% median quantile is different for each curve and we may suppose at first inspection that the red supplier is better than the blue one.

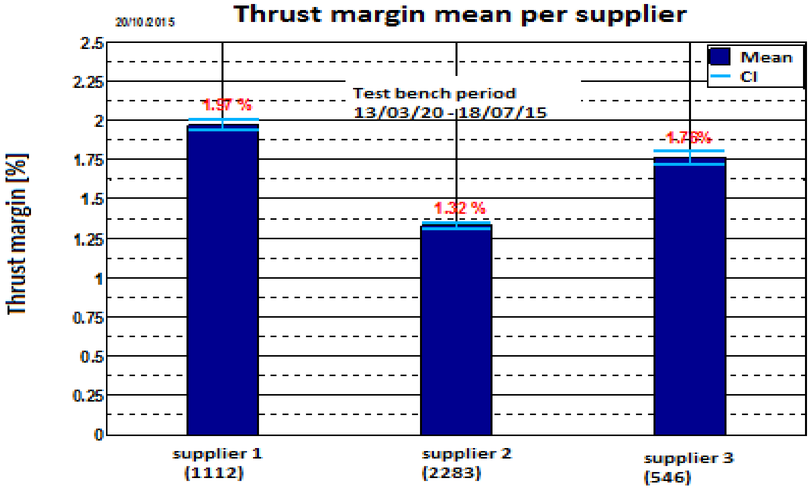

Figure 3: Mean of thrust margin by supplier with 95% confidences intervals.

As for the preceding comparison between suppliers thrust margins, a similar comparison may be observed for test bench (Figure 4) and for one of the most influence complementary technical adaptations on the measurement which is the cowl (Figure 5).

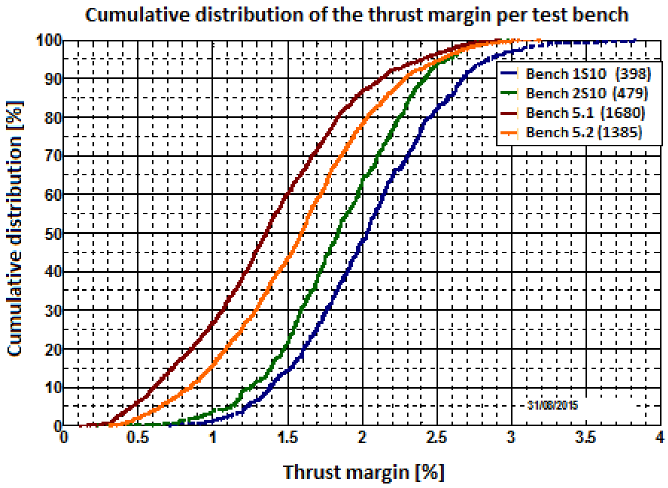

Figure 4: Repartition functions of the observed thrust margin measured on different bench test cells. As we can see the bench cell has a clear influence on the measurement because all produced engines are randomely distributed on each cell for the reception test.

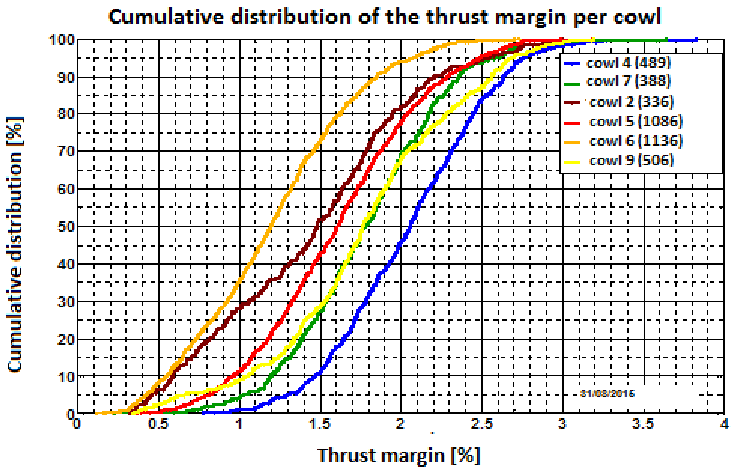

Figure 5: Different cowls may be used in each test cells, however, a cowl stays in the same site but this site may use different cells.

As illustrated in this last figure of the thrust margin evolution by cowl (Figure 5), there is a kind of ranking established between thrust margin cowls. However, this ranking depends of the cowl use period.

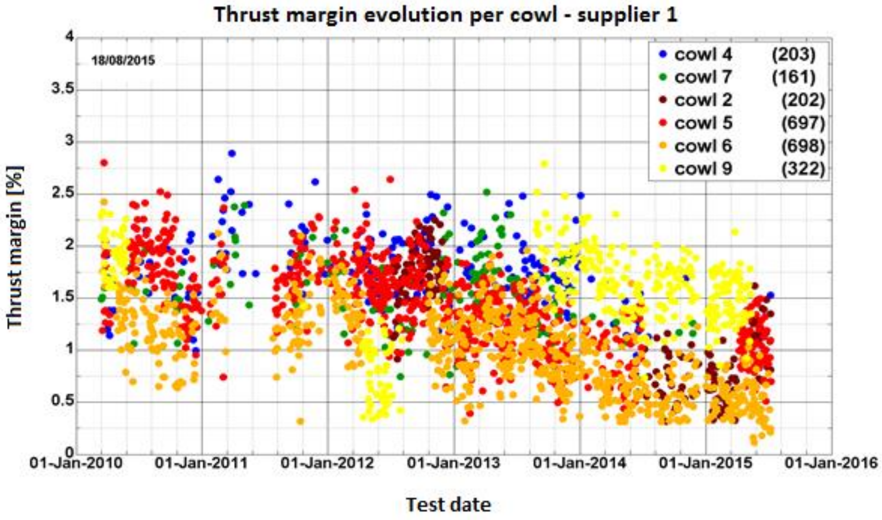

Figure 6: The thrust margin dependency on the cowl also depends on time intervals.

The reasons of cowl dependency on time is link to bench equipment maintenance procedures. We consider the bench context stable between maintenances and its effect constant during those time intervals. Hence the evolution observed during inter-maintenance interval is only due du the production trends which is still a mixture between suppliers. For model simplicity we consider the production trend linear per supplier during those small intervals. Hence, for a given turbofan production and bench test component use period, the thrust margin evolution is supposed linear.

Each input is defined by three observations $(y, t, k)$ where $y$ is a thrust margin measure, $t$ is a reception test date and $k$ is the component used on its given use period $k.$
For each component, we build a binary function $\delta_k(i)$ that gives 1 if the reception test $i$ is done using the component $k$ and send 0 otherwise.

So, looking only at one production type, we are resolving the equation system below:

$$y_i = \sum_k b_k \delta_k(i) \; + \; \phi(t_i) + \epsilon \tag{1}$$

Where $\phi$ is piecewise linear function representing thrust margin evolution, $b_k$ is the bias introduced by the component $k$ and $\epsilon$ is the measure error.

There is an initial indeterminate of the thrust margin that we are fixing with initial condition on the mean bias: $\bar{b} = \frac{1}{N} \sum_k N_k b_k \quad where\ N_k = \sum_i \delta_k(i)$ is the number of measures with the component $k$ and $N = \sum_k N_k$ is the total number of measurements.

Then, we have to take in consideration the existence of specific trends for each supplier, where the turbofan sets are different for each one but the bias should be identical. For each supplier $j$, a function $\phi_j$ is defined, we keep the same bias and use a supplier indicator function $\gamma_j$:

$$y_i = \sum_k b_k \delta_k(i) \; + \; \sum_j \phi_j(t_i) \gamma_j(i) \; + \epsilon \tag{2}$$

**A fast approximation**: We are fixing this problem in two steps, first we are describe the thrust margin evolution independently of the absolute level resulting of the component influence. Each measure append to the period when the receptions test condition are constants. This constant period is the intersection between two kinds of periods that we define as:

- Turbofan production period, between different linear trends of production (Figure 7).
- Component use period, between bench cells maintenances (Figure 8).

For each constant period, a mean point is placed in the middle of the period and the middle of the thrust margin as shown in Figure 9.
Then, we characterize the gap between the thrust margin measure and mean point, which is independent of the measurement conditions. Given that the functions $\left(\varphi_j\right)_j$ represent the thrust margin evolution mean model we just need to minimize equation (5) for each supplyer $j$ where $(\bar{t}_l, \bar{y}_l)$ are the coordinate of the selected mean point and $\tau_l$ a binary indicator function of the $l$ period.

$$\hat{\varphi}_j = Arg \min_{\varphi_j} \left\{ \sum_{l,i} \gamma_j(i) \tau_l(i) [(y_i - \bar{y}_l) - (\varphi_j(t_i) - \varphi_j(\bar{t}_l))]^2 \right\} \tag{3}$$

This model of piecewise slopes should be initialized with an indeterminate level as described previously: this first step just help identifying the slopes and change points for each supplier and stable period.

Once the evolution mean model is done, in the second step, we identify the mean bias introduced by the test bench components and the turbofan origins. We define a reference production $j_0$ for which the bias is supposed equal to zero.

$$(\hat{b}_k) = Arg \min_{(b_k)} \left\{ \sum_{i,j} \gamma_j(i) \left[ y_i - \varphi_j(t_i) - \sum_k b_k \delta_k(i) \right]^2 \right\} \tag{4}$$

And compute the normalized thrust margin

$$\hat{y}_i = y_i - \sum_k \hat{b}_k \delta_k(i) \tag{5}$$

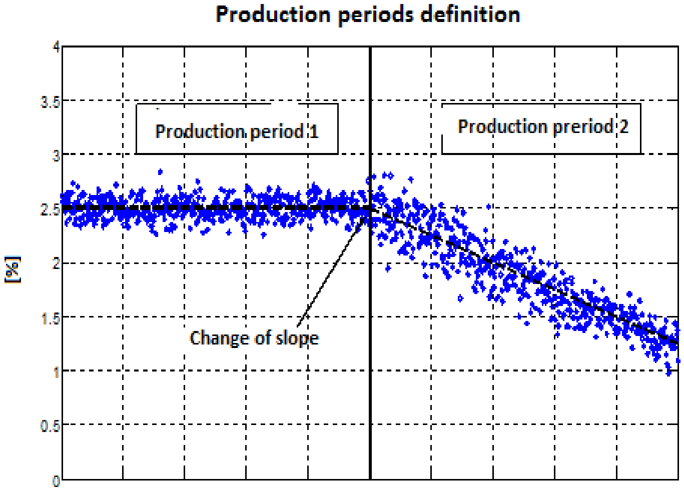

Figure 7: For a first try, the trend changes are visually identified by experts. Stable linear production for each supplier is supposed between two of those changes.

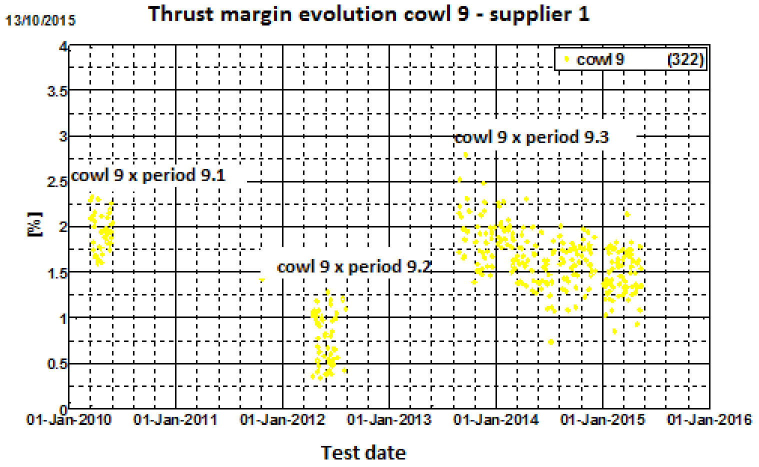

Figure 8: Intervals of cowls and cells used defined as inter-maintenance periods. On this graph one clearly see the difference of the mean thrust margin observed during each of those intervals. However, even if those measurements are coming from only one provider, its production trend may have change.

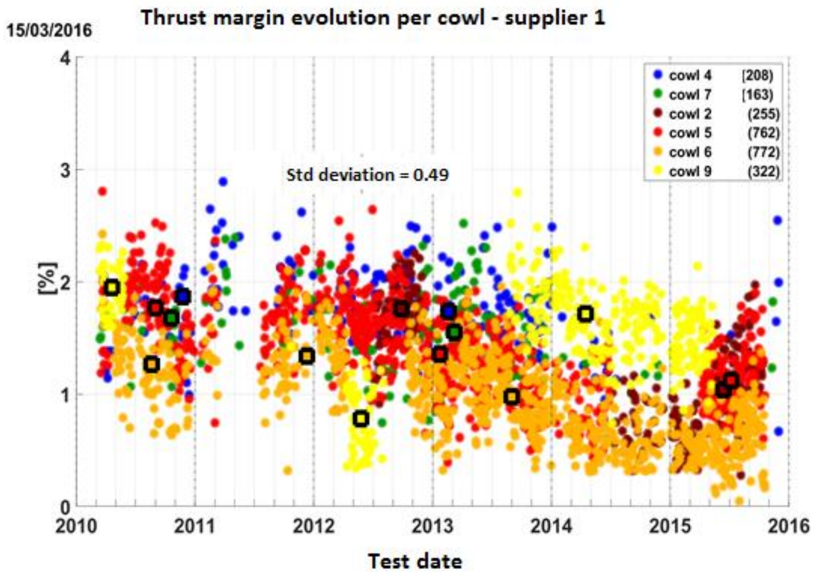

Figure 9: A mean margin is computed for each period intersection. This mean value is assign to a supplier stable tendency and a context inter-maintenance period.

**Results:** Concretely, the application of this method has made it possible to reduce by about a factor of 2 the dispersion of the thrust margin, hence achieving a gain in accuracy of the measure by 50%, as shown in the examples below: Figure 10 shows the initial values measured for the margin of engines produced by a given supplier and the Figure 11 present the identification of the trends and the reduction of variance.

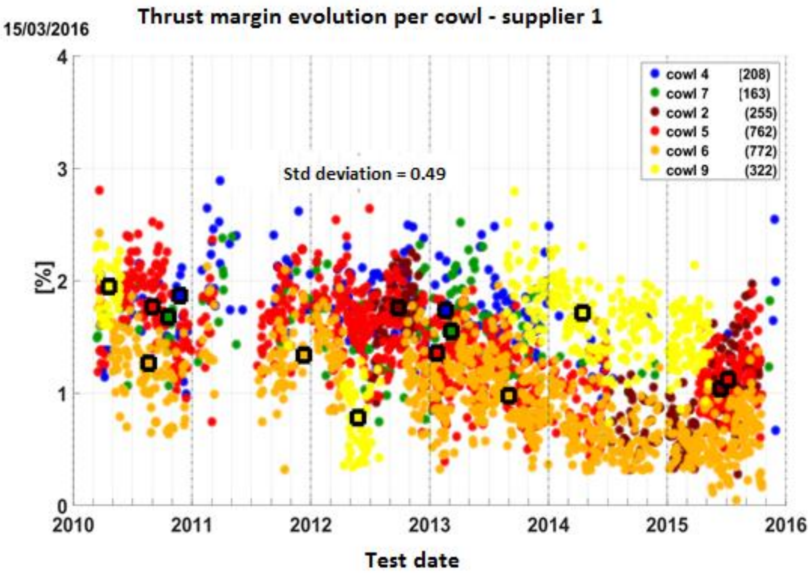

Figure 10: Initial observation of the thrust margin for a given supplier. Colors represent different cowls and benches.

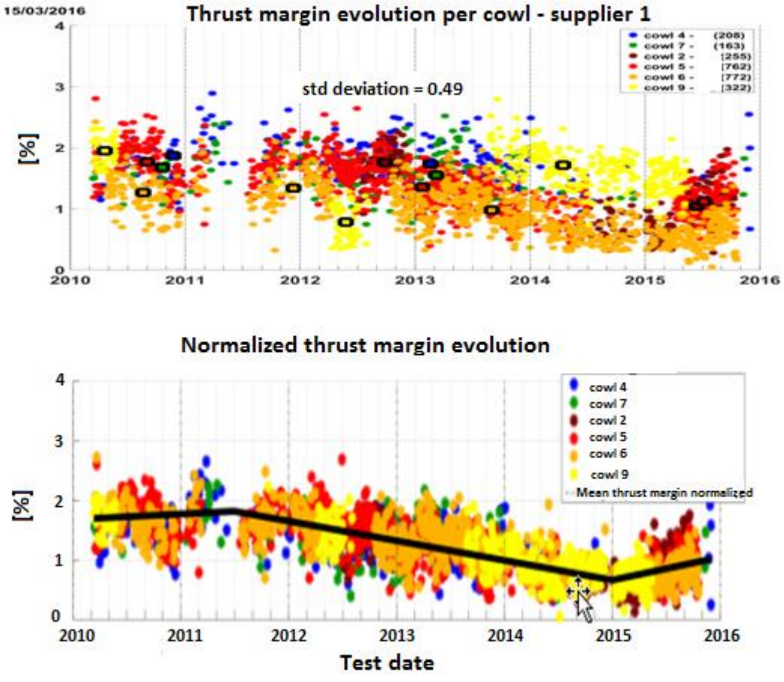

Figure 11: The same observation as on Figure 10 but after renormalization using our model with the piecewise linear model drawn as a black line.

Otherwise, we compute the bias for each test bench component, as shown in the figures below cowl and test bench.

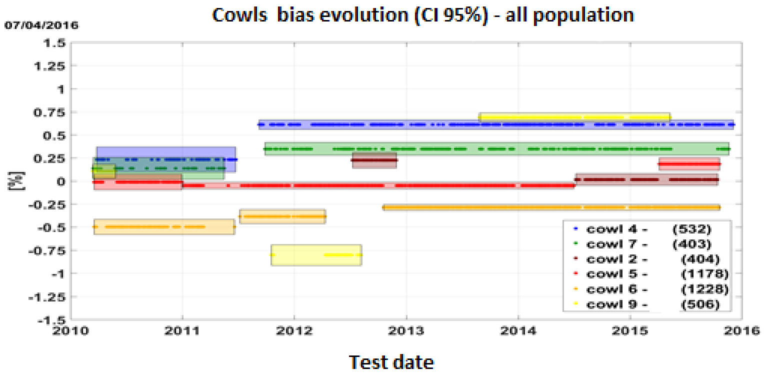

Figure 12: Evolution of the bias corresponding to cowls for different inter-maintenance intervals.

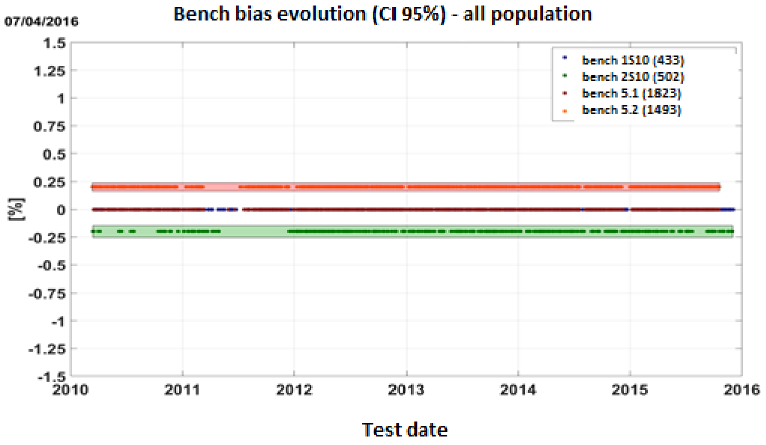

Figure 13: Computation of the benches bias during the period of analysis.

**Conclusion**: This study of the thrust margin trend allow us to build a new application used to calibrate our bench test cells and normalize our results. Moreover, we are now able to identify specific trends per supplier and emit alerts if necessary.
Once a real and objective computation of the thrust was available it becomes possible to check the dependencies with the geometry of the fan blades and then understand the second order characteristics that let us define better fabrication process and inform our suppliers.

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