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Overestimation of conformity assessment risks in legal requirements of weighing instruments

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ABSTRACT
This paper examines the risks for producers and consumers of non-automatic weighing instruments. It compares two scenarios: one where only the maximum permissible error requirement of the standard weights is considered during the computation of measurement uncertainty and another where the standard uncertainty of the weights is also involved. By quantifying these risks, the study sheds light on the potential implications for both producers and consumers. The results shows that in general, the producer and consumer risks are both wrongly estimated for the use of only the maximum permissible error location criterium. The overestimation founded reached levels higher than 20 %.

Section: RESEARCH PAPER

Keywords: NAWI; MPE; conformity assessment; global risk

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1. INTRODUCTION

OIML recommendation R 76-1 [1] states that a Non-Automatic Weighing Instrument (NAWI) must accomplish that its error of indication is at most equal to the corresponding Maximum Permissible Error (MPE) regard its load and accuracy class. The three metrological controls for conformity consist of type approval, initial and subsequent verifications, and service inspections.

The MPE for NAWIs for the type of approval and initial and subsequent verifications are the same, and they are half the ones for the service inspections [1]. On the other hand, for any NAWI produced that is chosen in a random way, there are risks of non-conformity wrong decisions that concerns both the producer and the consumer of the NAWI. The bad decision could be to accept a non-conforming instrument (risk to the consumer) or to reject a compliant device (risk to the producer) [2], [3].

During the computation of the conformity assessment the measurement uncertainty could be considered [2]-[4]. The use of guard-bands defined by a (sub)multiple of the expanded measurement uncertainty has been proposed and exemplified for a long time [2]-[5]. Even more, the use of Bayesian inference if there is available prior information about the statistical behavior of the measurand has also been encouraged [4], [5].

Some papers have addressed the producer/consumer risks computations for NAWIs. Efremova [6] uses the measurement uncertainty on the verification of multi-interval scale of Class III [1]. The uncertainty was not estimated in explicit form, but thorough the use of the ratio of the MPEs for the NAWI and the standard used for the metrological control. In that work, no previous knowledge of the measurand was considered in the risk's calculations. Weißensee et al. [7] show an example on the risk conformity assessment calculation for a laboratory scale of accuracy class 1 [1]. They used the measurement uncertainty value derived only from the combination of the MPE of the NAWI and an assumed capability measurement index, C_m [2]. The previous knowledge of the measurand was given through the process capability index, C_p [8]. Medina [9] reports that the risk of the producer for NAWIs could be as high as 40 %, while the risk of the consumer stays at 8 %. She computes the measurement uncertainty from the most important contributors to the type approval and the service inspection metrological controls. The prior information of the measurand was based purely on the type approval process of the NAWIs.

Example E2.5 from Greenwood et al. [10] contains cases related to the conformity assessment of NAWIs was included in a recent compendium of comprehensive examples related to using measurement uncertainty good practices. Example E2.5 warns about using the MPE values as substitutes for the measurement uncertainty values for traceability purposes. It gives an initial insight into the overstating of the measurement uncertainty. Even when the numerical example included in Table E2.5.1 from [10] is arbitrarily defined, it perfectly clarifies the point.

This paper quantifies the effects on the risks for the producer and the consumer when only the MPE (referred also as 'only-MPE') requirement of standard weights is considered during the computation of the measurement uncertainty (u_m) used in the NAWI conformity assessment, compared against when the standard uncertainty of the weights is also considered using guard bands. The study was extended to three different levels of the so-called guard band multiplier (r). The results show that, in general, the producer and consumer risk are both wrongly estimated when only the MPE location criterium is used.

In Section 2 we will state the specification limits for the instruments according to the metrological controls. Section 3 has the methodology used for the computation of the risks of non-conforming statement of the NAWIs condition. The Section 4 includes the results obtained with two different software used and discuss the numbers and figures. Finally, in Section 5 the main findings of this work are summarized.

2. MPE FOR NAWIS

Here, it was assumed that the manufacturing of the NAWI already conforms to the approved type [1]. Additionally, only the MPE considered for the service inspection will be analysed, given that this is the only legally relevant, as explained in [11].

In [1], it is stated that the MPE only could take the values of 0.5 e, 1.0 e, or 1.5 e for the type approval or verification, and double those values for the in-service inspection, where e is the verification scale interval of the instrument. In this work, it will be assumed that e is equal to the resolution of the NAWI or its actual scale interval, despite the type of instrument or accuracy class.

The tolerance limits (T_L, T_U, lower and upper, respectively) will be always equal to $\pm MPE$ for service inspection, while the acceptance limits (A_L, A_U, lower and upper, respectively) will be calculated according to the guard band multiplier chosen in such a way that $T_L \leq A_L$ and $A_U \leq T_U$ always. Figure 1 illustrates the parameters involved.

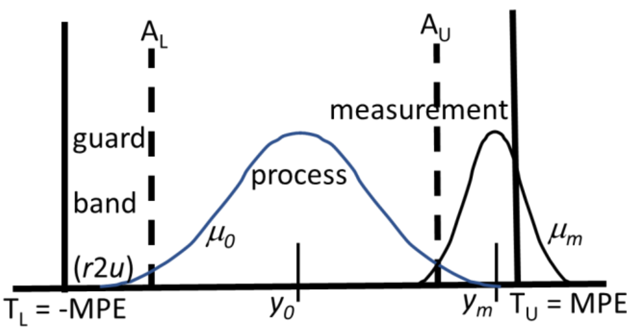

Figure 1. Surface response for the probability of non-conformity for a particular NAWI when prior information is available. Case 2. MPE = 1 e. r = 0. C_p = 1.33.

3. METHODOLOGY

Three cases for calculating the non-conformity probability risks are analysed here, depending on the availability of the previous information on the NAWIs. In the Case 1, the probability of non-conformity for a not available previous knowledge of the NAWI was computed. For Case 2, the production process of the NAWIs is assumed to be well characterized by a normal probability density function (PDF). A particular assessed NAWI is considered, and the quantitative information from the production process is used. Finally, in the Case 3, similar conditions regard previous knowledge are held, but this time the NAWI is chosen at random from the manufacturing process.

We compared the risks calculated for all three cases by solely using the MPE value of the standard weight employed for the conformity assessment of NAWIs to the risks obtained when considering all the calibration data [10].

3.1. Probability of non-conformity and specific risks (Cases 1 & 2)

The formulae for calculating the probability of conformity, which determine the probability of non-conformity for Case 1, are provided in Sections 7.2, 7.4, and Annex A of [2]:

$$1 - p_c = 1 - \Phi\left(\frac{T_U - y}{u}\right) + \Phi\left(\frac{T_L - y}{u}\right), \quad (1)$$

where p_c is the probability of conformity, $y = y_m$ is the average result of the measurement, and $u = u_m$ is the corresponding measurement uncertainty. $\Phi(z)$ is the standard normal distribution function (see Annex A in [2]). In this case, $y_m \in [-MPE, MPE]$ for the service inspection metrological control.

In Case 2, assuming that a previous NAWI follows a normal PDF with mean y_0 and variance u_0^2, equation (1) brings the *specific consumer´s risk*, given the values for y and u are now defined by:

$$u = \frac{u_0\, u_m}{\sqrt{u_0^2 + u_m^2}}, y = \frac{\frac{y_0}{u_0^2} + \frac{y_m}{u_m^2}}{\frac{1}{u^2}} \quad (2)$$

The *specific producer´s risk* is p_c. Here, $y_m \in [-MPE, MPE]$ again, and $y_0 \in [A_L, A_U]$ for the corresponding metrological control.

3.2. Global risks (Case 3)

Annex A from [2] describes the equations for the *global* risks for consumers and producers. These are rather complex

Table 1. Uncertainty components for in service inspection expressed as function of scale interval e, MPE and the guard band multiplier r values.

Uncertainty contributor	Formula
Resolution	$e / (2 \cdot \sqrt{3})$
Temperature	$e / (2 \cdot \sqrt{3})$
Repeatability	$MPE / (2 \cdot \sqrt{3})$
Eccentricity	$MPE / (2 \cdot \sqrt{3})$
Weight calibration, only MPE	$MPE / \sqrt{3}$
Weight calibration, MPE + standard uncertainty	$(MPE / \sqrt{3}) \cdot \sqrt{1/12 + (1 - r / 3)^2}$
Tested parameters	**Values**
MPE	1 e – 2 e – 3 e
Guard band multiplier, r	0 – 0.5 – 0.75 – 1.0

Table 2. The three cases under study in this paper.

Case	Assumptions	Input parameters
1	Rectangular PDF of MPE, Normal PDF of std weights uncertainty, Normal PDF of y_m, intervals centred at zero.	e = 1, all of Table 1 $y_m = -MPE$ to MPE
2	All of Case 1, Normal PDF of y_0, centred production process, a particular measured NAWI accepted as conforming.	All of Case 1, $y_0 = -MPE$ to MPE, C_p = 0.67 to 1.33
3	All of Case 2, but for a NAWI chosen at random from the production process.	All of Case 1, $y_0 = A_L$ to A_U, C_p = 0.67 to 1.3

equations that will not be replicated here. Generally, it is preferred to solve these equations with numerical methods, and in this work the software CAsoft [12] was employed for that task. Other mathematical software could also be used [9], [13].

In this case, the acceptance limits vary according to $[A_L, A_U] \subseteq [-MPE, MPE]$, and $y_0 \in [A_L, A_U]$ for the corresponding metrological control.

3.3. Uncertainties determination

The NAWIs used in commercial transactions are usually regulated by the measurement law of every country. Morinaka [14] identified the contributions made by the performance of the NAWIs (service inspection in [1]) to the measurement uncertainty of the NAWIs undergoing conformity assessment (u_m) in this study. The PDF of every contributor are explained in [1] and derived in [15]. Even when [15] is a guide for calibration, the affectation on the NAWIs measurements is essentially the same.

Table 1 shows the final relationship of every uncertainty contributor as (sub)multiples of the verification scale interval, *e*, the MPE values, and the guard band multiplier chosen, *r*.

Finally, the prior knowledge uncertainty from the manufacturing process of the NAWIs comes from the process capability index, C_p [8]:

$$C_p = \frac{T_U - T_L}{6\,\sigma} = \frac{+MPE - (-MPE)}{6\,u_0}, \tag{3}$$

Table 3. Measurement uncertainty (u_m) values, expressed as *e* factors, as a function of the MPE and the guard band multiplier, *r*.

MPE	*Only MPE, r* = 0	*r* = 0.5	*r* = 0.75	*r* = 1.0
1	0.81	0.77	0.74	0.71
2	1.47	1.37	1.30	1.24
3	2.16	2.00	1.90	1.80

where σ is the empirical standard deviation of the manufacturing process, which could be used as an estimate (u_0) of the NAWIs population standard deviation [7].

In terms of its C_p value, a manufacturing process is considered 'potentially capable' if $C_p \geq 1.33$, 'marginally capable' when $C_p \geq 1.0$, and 'uncapable' if $C_p < 1$ [8]. These three conditions of the manufacturing process of NAWIs will be assessed through the corresponding u_0 values. Table 2 contains an overview of the three cases studied in this work, their assumptions, and their input parameters.

4. RESULTS AND DISCUSSION

4.1. Measurement uncertainty overestimation

Table 3 shows the measurement uncertainty, u_m, for the combination of MPE values and guard band (sub)multiple, *r*, including no guard banding, i.e., only the MPE requirement value of the weights is considered in quantifying the uncertainty.

As can be seen, the overestimation of the measurement uncertainty ranges from 6 % to 20 %, approximately when a rectangular PDF with limits equal to [–*MPE*, +*MPE*] is the only contributor to the uncertainty. Greenwood et al. [10] claim that, in general, the overestimation could be as high as 50 %. And the use of only the MPE requirement for the weight calibration could be an interpretation of the Annex A.2.3 in [16].

4.2. Case 1. Probability of non-conformity

Figure 2 and Figure 3 show the results for the probability of non-conformity computations for two different values for the MPE in service inspection of the NAWIs. In Case 1, the abscissa only shows assumed values for y_m normalized by the corresponding MPE value.

A value of $y_m = 0$ indicates that the measurement result lies exactly in the middle of the [–*MPE*, +*MPE*] interval of

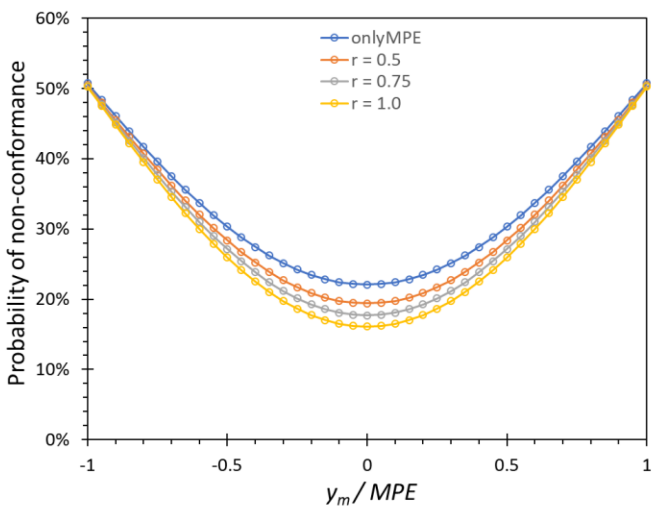

Figure 2. Probability of non-conformity for different guard band multiplier *r*, for an assumed inexistent prior information. Case 1. *MPE* = 1 *e*.

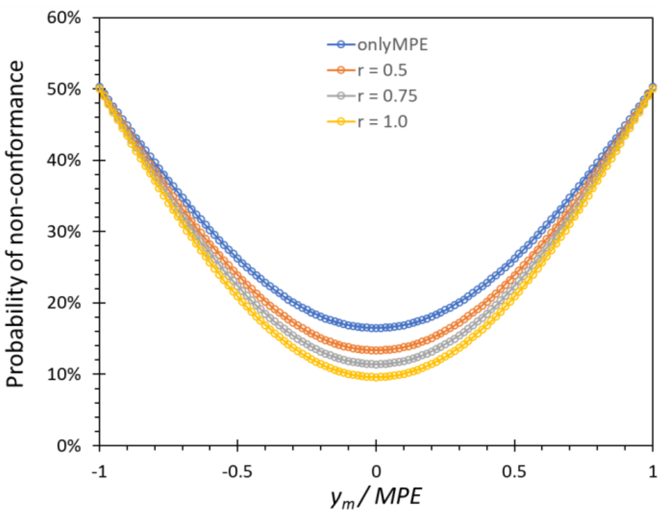

Figure 3. Probability of non-conformity for different guard band multiplier *r*, for an assumed inexistent prior information. Case 1. *MPE* = 3 *e*.

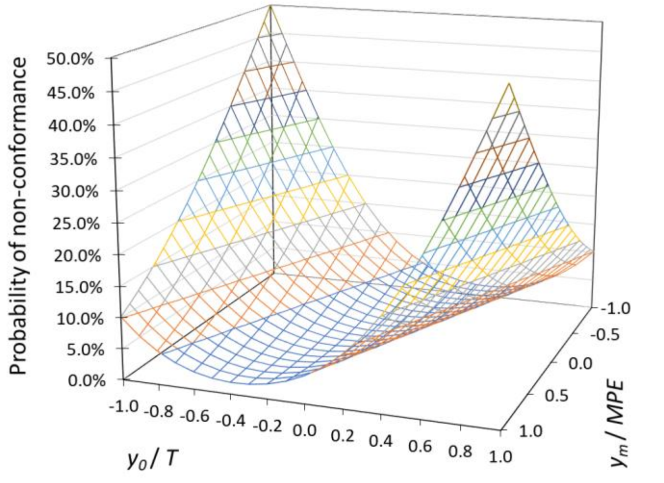

Figure 4. Surface response for the probability of non-conformity for a particular NAWI when prior information is available. Case 2. *MPE* = 1 *e*. *r* = 0. C_p = 0.67.

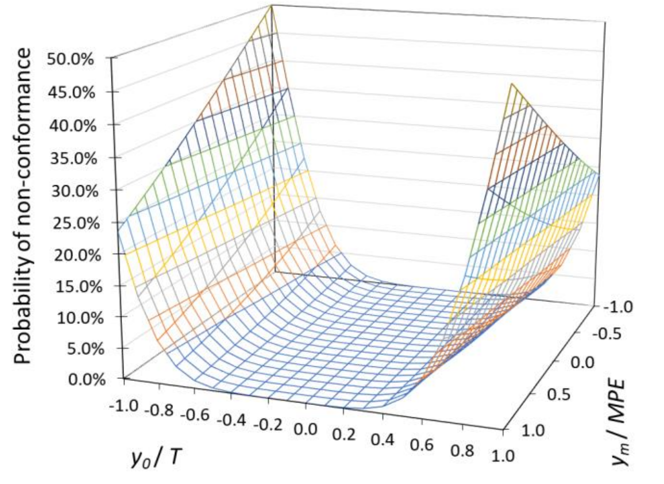

Figure 6. Surface response for the probability of non-conformity for a particular NAWI when prior information is available. Case 2. *MPE* = 1 *e*. *r* = 0. C_p = 1.33.

specifications. As expected, the minimum of the graphs occurs at this value. On the other hand, at the extreme value the called 'shared risk' arises and the probability for producer and customer splits on the fifty-fifty way.

Figure 2 and Figure 3 exhibit a significant overestimation of non-conformity probability (customer risk) when relying solely on MPE information. This overestimation can reach values as high as 7 %.

Also, for Figure 2 and Figure 3, the higher the value of the guard band, the greater the difference between the values of probability. This obeys to the fact that for broader guard bands the Gaussian PDF standard uncertainty component of the weight calibration contribution (see Table 1) becomes more significant.

Finally for this Case 1, the minimum probability of non-conformance decreases as the MPE increases, due to the longer distance from the centre of the assumed y_m value to the tolerance limits in equation (1).

4.3. Case 2. Specific risks

Figure 4 to Figure 7 show the resulting graphs for some combinations of *r* and C_p extreme values, for the tolerance *MPE* = 1 *e*. Similar results were obtained for the other two values of MPE, and the corresponding graphs are available as complementary material of the paper. Extreme parameters values were selected for strategy to get conclusions about the results shown. However, the graphs for the intermediate values of *r* and C_p are also available under request.

On the four graphs, the 'opposite extreme' situation is when the prior information PDF has a mean equal to one extreme of MPE while the measurement result has a mean on the opposite extreme MPE value. Hence, if $y_0 = T_L = -MPE$ then $y_m = +MPE$, and vice versa. On the other hand, the 'same extreme' situation occurs when the values of y_0 and y_m are both equal to $-MPE$ or $+MPE$. This situation gives us the 'shared risk' again, like in Case 1.

Comparison between Figure 4 and Figure 5, where the only change is the value of the guard band multiplier from zero (only MPE considered) to 1 (guard band equals the expanded uncertainty), shows half the probability of non-conformity for the guard-banded condition in the opposite extreme situation. Therefore, there are more points with a probability of non-conformity lower than 5 % in Figure 5 than in Figure 4. That is

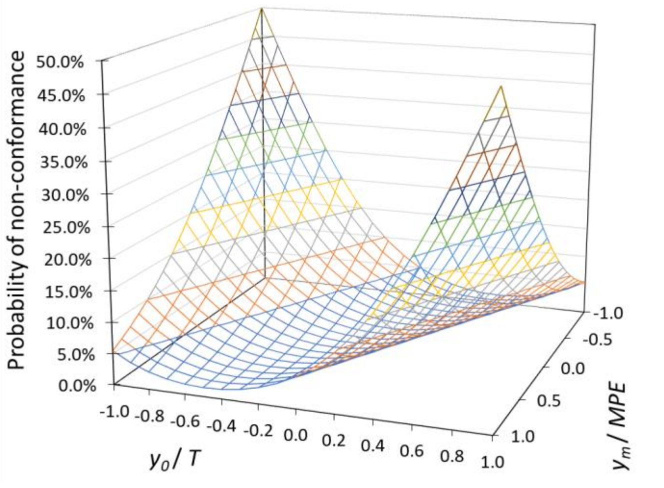

Figure 5. Surface response for the probability of non-conformity for a particular NAWI when prior information is available. Case 2. *MPE* = 1 *e*. *r* = 1. C_p = 0.67.

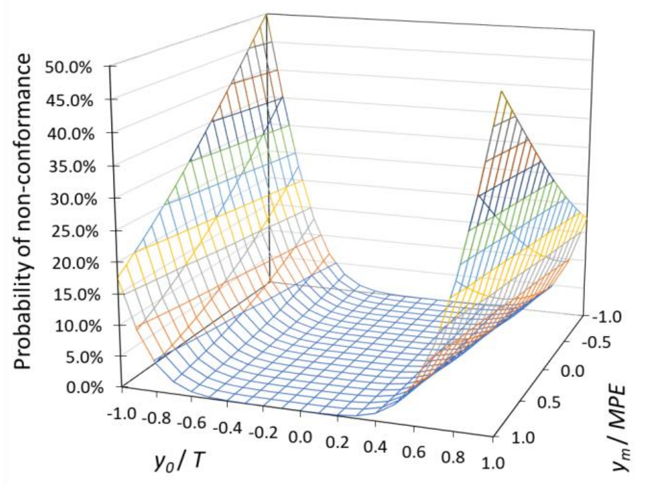

Figure 7. Surface response for the probability of non-conformity for a particular NAWI when prior information is available. Case 2. *MPE* = 1 *e*. *r* = 1. C_p = 1.33.

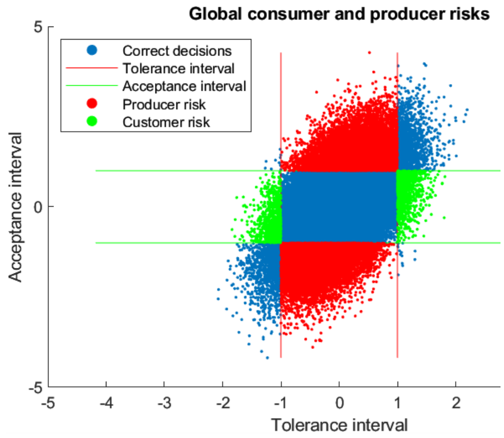

Figure 8. CAsoft® Monte Carlo simulation results graph for global risks. Case 3. MPE = 1 e, r = 0, C_p = 0.67, y_0 /A = 0.

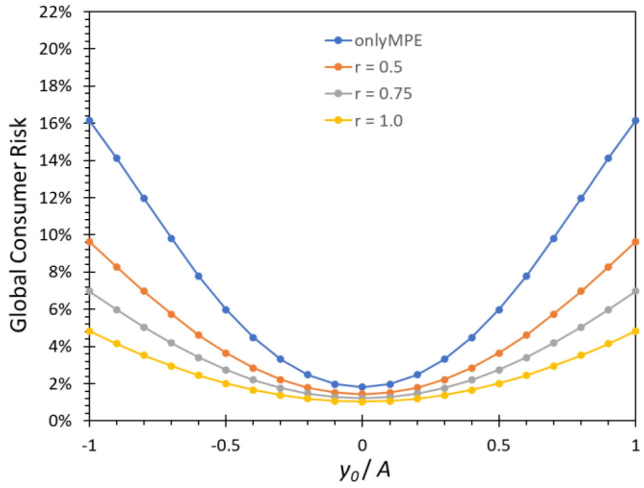

Figure 10. Global consumer risk curves for the span of y_0 in [A_L, A_U] at different values of the guard band multiplier, r. Case 3. MPE = 1 e, C_p = 0.67.

because the guard band given by r = 1 protects the consumer with lower risk values.

Figure 6 exhibits a clearly flatter surface than Figure 4, even when the parameters MPE and r = 0 are the same in both. However, the flatness occurs regard the y_0 values, and a bigger value of C_p implies less dispersion in the prior PDF. This is the reason why higher values of y_0 could be closer to the tolerance limits, T = [T_L, T_U], while keeping a low probability of non-conformance values.

Finally, Figure 7 presents a 'full' guard banded flatter surface response, compared to the Figure 5, which has similar parameter values (MPE = 1 e, r = 1). Explanation have been exposed in previous paragraph. Also, Figure 7 appears to have lower probability values on the 'opposite extremes' (17.6 %) than their correspondents in Figure 6 (23.6 %). Notice that the difference in the probability of non-conformity (6 %) is like the overestimation found in the Case 1.

4.4. Case 3. Global risks

Figure 8 and Figure 9 exhibit the results graph that CAsoft [12] yields as part of its global risks analysis option. In Figure 8 the point's cloud is symmetrical regards both pairs of limits: tolerance and acceptance. This is because the input value for the mean of the manufacturing process of the NAWIs was selected centred (for this trial). In contrast, Figure 9 is not symmetrical because the input value for y_0 = A_U, so the prior PDF of the measurement result is centred in A_U.

Even when the process in Figure 8 is centred on tolerance and acceptance intervals, and the process in Figure 9 is loaded towards one acceptance limit, their consumer risks are very similar in magnitude (around 2 %), because the higher value of C_p in the process of Figure 9 compensates its decentralization, protecting the costumer.

Figure 10 and Figure 11 exhibit the global consumer and global producer risks graphs, respectively, for different values of the guard band multiplier. In Figure 10, higher value for the global consumer risk reaches 16 % for the only-MPE situation regard the estimation of measurement uncertainty (r = 0), whereas that level of consumer risk drops even to 5 % at the same y_0 location on any of the limits of acceptance, A_L or A_U. When y_0 is located at the centre of the acceptance interval, the difference between the global consumer risk as function of the guard band multiplier tends to be 1 % at most. However, it is important to note that the difference between consider only the MPE and to use a guard band (sub)multiple grows in a power fashion, such that the difference is minimal for a manufacturing centred process but is almost four times if the process is totally overturned on one of its acceptance limits.

Figure 11 shows notoriously higher values for the global producer risk than the corresponding for the global consumer

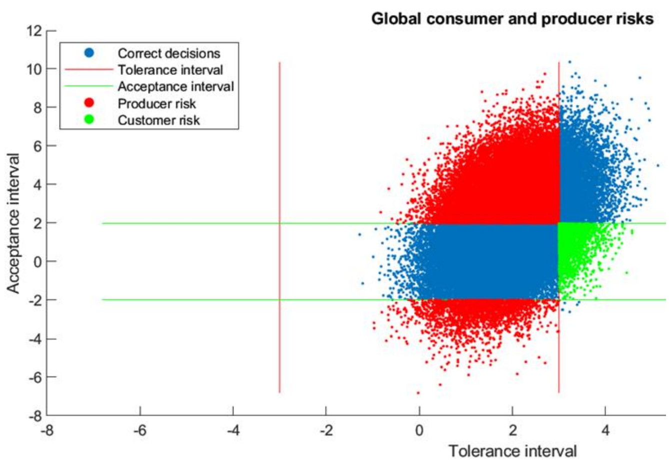

Figure 9. CAsoft® Monte Carlo simulation results graph for global risks. Case 3. MPE = 3 e, r = 1, C_p = 1.33, y_0 /A_U = 1.

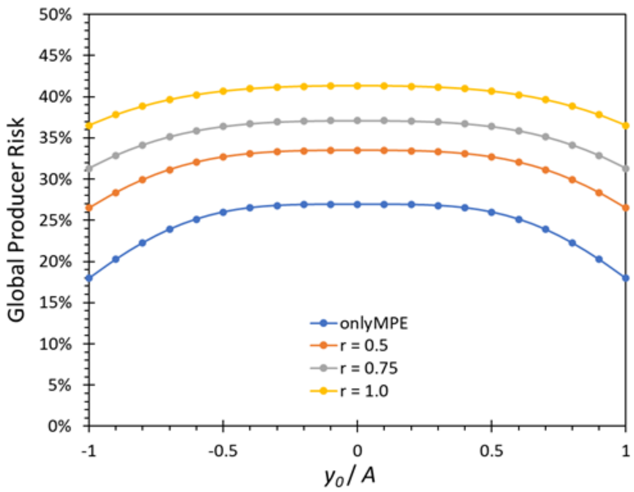

Figure 11. Global producer risk curves for the span of y_0 in [A_L, A_U] at different values of the guard band multiplier, r. Case 3. MPE = 1 e, C_p = 0.67.

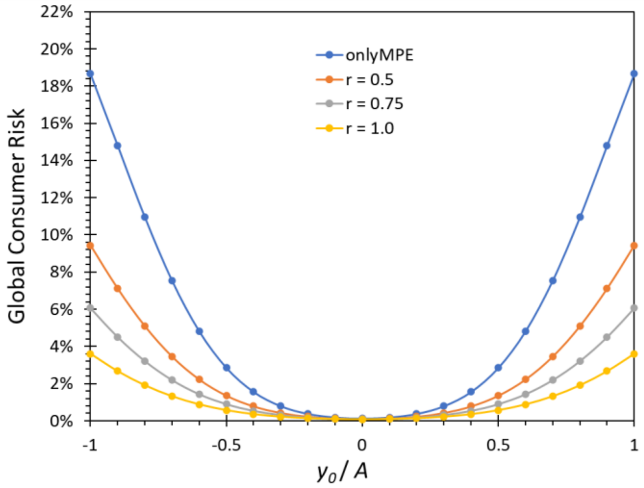

Figure 12. Global consumer risk curves for the span of y_0 in [A_L, A_U] at different values of the guard band multiplier, r. Case 3. MPE = 1 e, C_p = 1.

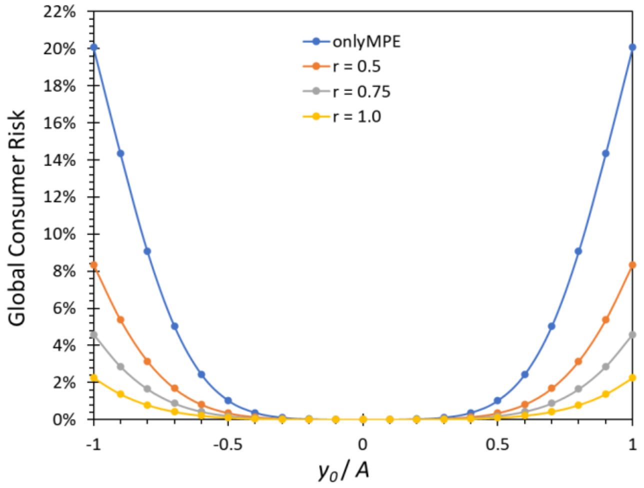

Figure 14. Global consumer risk curves for the span of y_0 in [A_L, A_U] at different values of the guard band multiplier, r. Case 3. MPE = 1 e, C_p = 1.33.

risk of Figure 10. That agrees with the findings in [9] and [17]. Also, in Figure 11 the only-MPE consideration could result in a misleading lower global producer risk of up to 20 % less when compared to a $r = 1$ guard band. This is an expected result since the overestimation caused by the only-MPE approach affects the measurement uncertainty, and this in turn has a direct effect on the consumer risk, but the inverse effect on the producer risk, due to the guard banding. So, higher values of global consumer risk correspond to lower values of global producer risk.

Moreover, unlike Figure 10, the curves for global producer risk do not approach each other along the acceptance interval. And even when the expected coupled behaviour: consumer risk increases → producer risk decreases is accomplished, there is a kind of central plateau on the producer risk graphs that almost reach the 50 % of the acceptance interval.

Figure 12 and Figure 13 have the graphs corresponding to the global consumer risk and the global producer risk, respectively, for the same situation of Figure 10 and Figure 11, but for a marginally capable process with $C_p = 1$.

Figure 12 has similar characteristics than Figure 10, but in this case the higher value for the global consumer risk reaches more than 18 % for the only-MPE ($r = 0$) condition, whereas that level of consumer risk drops lower than 4 % at the same y_0 location on any of the limits of acceptance, A_L or A_U. When y_0 is located at the centre of the acceptance interval, the difference between the global consumer risk as function of the guard band multiplier is now negligible. So, the maximum overestimation of the global consumer risk is now 14 %, unlike 11 % for Figure 10.

Figure 13 keeps high values (20 % to 44 %) for the global producer risk. Here, the only-MPE consideration could result in a misleading lower global producer risk of up to 24 % less when compared to the guard band condition $r = 1$.

For the parameter values of Figure 13, maxima over the semi-interval of acceptance, $y_0 = 0$ to $y_0 = A_U$, occurs (it is the same for the A_L side). When this happens, two different values of y_0 could yield the same value for the global producer's risk, but only one of them will have a lower global consumer risk. The maximum is more pronounced for the only-MPE condition.

Finally, Figure 12 and Figure 13 have the graphs corresponding to the global consumer risk and the global producer risk, respectively, for the same situation of Figure 10 to Figure 13, but for a good capacity process with $C_p = 1.33$.

Figure 14 shows case the higher value for the global consumer risk as 20 % for the only-MPE condition, whereas that level of consumer risk drops nearly 2 % at the same y_0 location on any of the limits of acceptance, $A_{L,}$ or A_U. Again, when y_0 is located at

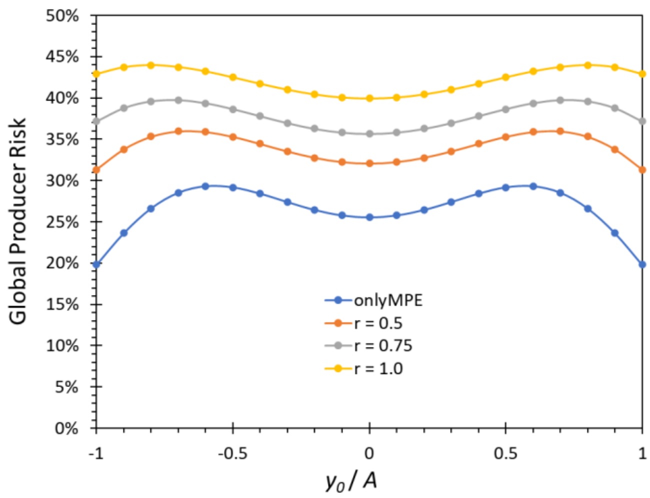

Figure 13. Global producer risk curves for the span of y_0 in [A_L, A_U] at different values of the guard band multiplier, r. Case 3. MPE = 1 e, C_p = 1.

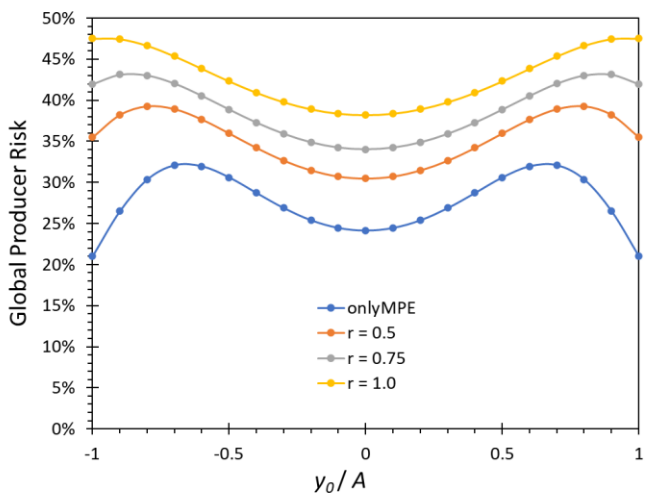

Figure 15. Global producer risk curves for the span of y_0 in [A_L, A_U] at different values of the guard band multiplier, r. Case 3. MPE = 1 e, C_p = 1.33.

Table 4. Summary of main risk results. *MPE* = 1 *e*, *r* = 1. Cases 2,3: C_p = 1.33.

Case description	Only-MPE		Full calibration	
	Cons.	Prod.	Cons.	Prod.
Case 1. No prior information available on NAWI production process. *Probability of conformity* studied.	22 %	78 %	16 %	84 %
Case 2. Prior information available and *specific risks* for a particular NAWI studied.	24 %	76 %	18 %	82 %
Case 3. Prior information available and *global risks* for a random NAWI studied.	20 %	32 %	2 %	45 %

the centre of the acceptance interval, and for almost the semi-interval of acceptance, the difference between the global consumer risk as function of the guard band multiplier is practically zero. So, the maximum overestimation of the global consumer risk is now 18 %.

Figure 15 exhibits the highest values (21 % to 47 %) for the global producer risk. Again, the only-MPE consideration could result in an error on the global producer risk of up to 26 % less when compared to the guard band condition $r = 1$. The maxima over the acceptance semi-interval, $y_0 = 0$ to $y_0 = A_L$ (or A_U), are also reported here. Again, the maximum is more pronounced for the only-MPE condition.

These maxima phenomenon have been exposed from a different framework by Greenwood et al. in the Figure E2.5.5 in [10], where the curves relating the ratio of the measurement uncertainty that belongs to the only-MPE approach are plotted against C_m values (see the Introduction) and exhibit minima, for several values of the probability of conformance, p_c, which is closely related to the producer risk [2].

5. SUMMARY AND CONCLUSION

The use of the only-MPE criterium when estimate the measurement uncertainty of the weight calibration contribution during NAWIs conformity assessment have been evaluated against the inclusion of the full calibration information. Three cases were analysed, and their main risks results are summarized in Table 4. In addition, three different conditions were evaluated for the capacity of the production process through the process capacity index.

For case 1), the results of the probability of non-conformity range from 22.1 % (MPE = 1 *e*, $r = 0$) to 9.6 % (MPE = 3 *e*, $r = 1$). For case 2), the results of the consumer specific risks range from 23.6 % (MPE = 1 *e*, $r = 0$, $C_p = 1.33$) to 1.8 % (MPE = 3 *e*, $r = 1$, $C_p = 0.67$). For case 3), the results of the consumer global risks range from 20.1 % (MPE = 1 *e*, $r = 0$, $C_p = 1.33$) to 2 % (MPE = 3 *e*, $r = 1$, $C_p = 1.33$), whereas the results of the producer global risks range from 16.5 % (MPE = 3 *e*, $r = 0$, $C_p = 0.67$) to 47.5 % (MPE = 1 *e*, $r = 1$, $C_p = 1.33$).

The results shown an erroneous estimation of the producer and consumer risks for the only-MPE approach ($r = 0$), which agrees with other publications results. This misleading estimation could reach more than 20 % for the global producer risk when evaluating the same y_0 point (see Figure 15).

Future extensions of this work include an in-depth analysis of the maxima phenomenon present for the global producer risk.

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