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Dimensional XCT comparison campaign on an aluminium object

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Abstract

An x-ray computed tomography (XCT) interlaboratory comparison campaign, involving an aluminium-machined object, whose dimensions ($92 \times 78 \times 63$ mm^3) are significant for a 225 kV XCT system, was performed for the purpose of investigating the performances of industrial XCT systems for dimensional measurements in terms of accuracy, i.e. precision and trueness, and to evaluate the influence of the measurement protocol (i.e. measurement strategy), of the operator and of the software on the results by comparison to reference measurements. In this campaign, we came to the conclusion that the measurement strategy is predominant, except for distance; that the measurement process is affected by the operator only for cylindricity and coaxiality; that there is no or little influence of the software except for coaxiality and position; and that a volumetric Gaussian filter allows to improve the measurements only for some participants' measurements Furthermore, different behaviours, in terms of precision and trueness, are observed depending on the type of measurands when performed by different operators. The diameter measurements are reproducible with XCT, lower than 30 µm which corresponds to a subvoxelic factor of 2.5 and the trueness is lower than 22 µm. The distance measurement is also reproducible with XCT, 15 µm which corresponds to a subvoxelique factor of 4.9 and the trueness is 8 µm. For these mesurands, their measurements do not depend on the used XCT system. However, the XCT reproducibility for cylindricity, coaxiality and position is worse as well as of the trueness except for the position which has a trueness of 1 µm. The process measurement should be revised regarding cylindricity and coaxiality measurements. Finally, overall, the ability of the participants to perform measurements with XCT, whatever their system, is statistically comparable except for a few measurements.

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Keywords: dimensional measurements, x-ray computed tomography, comparison campaign, round robin

(Some figures may appear in colour only in the online journal)

1. Introduction

Additive manufacturing (AM) gives the opportunity to fabricate parts with very complex geometries, including internal features. For material, but also dimensional quality inspections, of such complex parts, x-ray computed tomography (XCT) is the only adapted non-destructive method, hence the recent popularity of XCT in the AM industry. This industrial popularity brings out the need for XCT capability evaluation in terms of dimensional measurements.

The XCT working group of the French Confederation for non-destructive testing (Cofrend) [1] performed a dimensional XCT interlaboratory comparison campaign on a large aluminium-machined object. The purpose of this comparison was to investigate the performances of industrial XCT systems [2] for dimensional measurements [3, 4] in terms of accuracy, i.e. precision [5] and trueness [6], and to evaluate the influence of the measurement protocol, of the operator, and of the software on the results by comparison to reference measurements.

Dewulf *et al* has performed an extensive review about dimensional metrology involving XCT [7]. One of the section is dedicated to 'Interlaboratory comparisons for dimensional and geometrical feature metrology' [8–13]. These interlaboratory comparisons involved several participants and several different XCT systems to perform dimensional measurements on various objects, and the comparison to reference measurements has been made. However, it seems that none of these comparison campaigns evaluates the influence of the measurement protocol, of the operator and of the software on the results by comparison to reference measurements. Furthermore, these comparison campaigns involved objects limited in dimensions to cube of 10 mm side, 15 mm diameter cylinder and 40 × 60 mm bracket, but also to external dimensions. In the present comparison campaign, the object's dimensions (92 × 78 × 63 mm) are significant for a 225 kV XCT system regarding correlated penetration power for aluminium. In addition, all measurands are internal dimensions.

The paper is structured as follows: the first section presents the different steps of the comparison campaign; the second section describes the circulating part in the comparison campaign; the third section is dedicated to the definition of the measurands; the fourth section reports on the calibration of the circulating part. Finally, the last two sections are related to the XCT dimensional measurements performed in the comparison campaign and their statistical analysis.

2. Description of the comparison campaign

Figure 1 displays the flowchart of the comparison campaign. Each participant carried out three independent scans of the object as well as the reconstruction of their three-dimensional (3D) image. Then, each participant performed the dimensional measurements of several measurands, on the 3D images, on their own, according to a first protocol (prot. 1). These first results were analysed and compared to reference measurements performed with a coordinate measuring machine (CMM). The high bias observed between XCT and CMM measurements led the working group to reconsider the measurement protocol to narrow the trueness. Thus, another protocol was elaborated (prot. 3) and had to be used by each participant to measure again the measurands. This new protocol (prot. 3) includes two majors changes: (1) increasing local searching parameters named 'Search distance' and 'Safety distance' in VGSTUDIO MAX to 1 mm, and (2) applying a volumetric Gaussian filter during reconstruction, before the segmentation, to reduce the noise. In addition, to evaluate the influence of this volumetric Gaussian filter, an intermediate protocol without applying the filter, was also implemented (prot. 2). Furthermore, each participant had also to provide their raw scans to VG and Zeiss such as they can carried out the dimensional measurements with VGSTUDIO MAX and GOM Volume Inspect, respectively. These different steps are summarized in figure 1 and the differences between the three different protocols are highlighted in table 1. Figure 2 explained schematically the

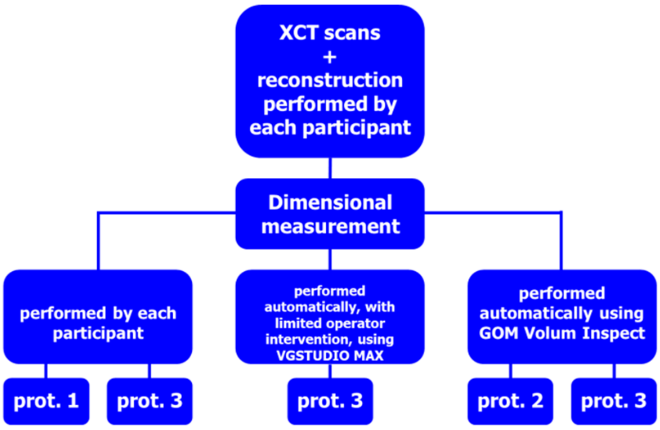


Figure 1. Flowchart of the comparison campaign.

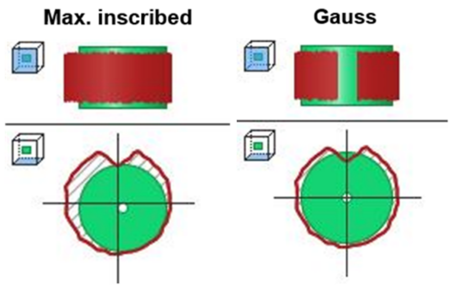


Figure 2. Difference between the two measurement methods implemented in the three protocols (GOM scheme).

Table 1. Differences between the three measurement protocols.

Geometry element	Fit properties	Prot. 1	Prot. 2	Prot.3
3D image		No filter		Volumetric Gaussian filter before segmentation
Cylinder	Method	Max inscribed except M1 Chebyshev	Gauss (least square) except M1 Chebyshev	
	Search distance (mm)	0.1	1	
	Safety distance (mm)	0.2	1	
	Max gradient (degree)	15	15[a]	
Plane	Search distance (mm)	0.1	1	
	Safety distance (mm)	0.2	1	

[a] This angle could be adjusted with GOM Volume Inspect.

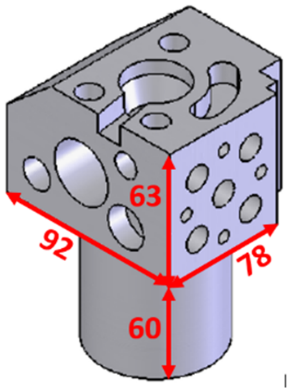
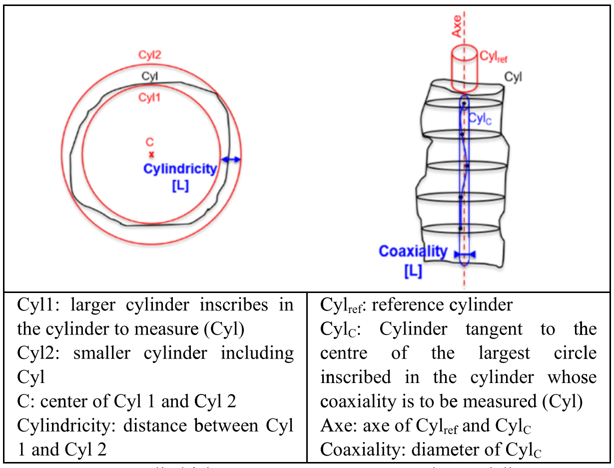


Figure 3. Numerical design and dimensional sizes of the CAD Cube (size are in millimetres).



a: cylindricity b: coaxiality

Figure 4. Schematic illustrations of the definition of cylindricity (a) and coaxiality (b).

difference between the two measurement methods implemented in the three protocols: maximum inscribed and Gauss.

3. Description of the circulating part

An aluminium-machined object (figure 3), named CAD Cube, was provided by Zeiss.

4. Definition of the measurands

Seven measurands were selected for the comparison campaign, including one distance, three diameters, one cylindricity (figure 4(a)), one coaxiality (figure 4(b)) and one true position. They are listed and described in table 2 and in annex 1.

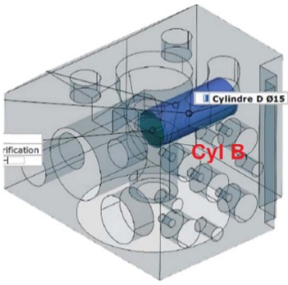
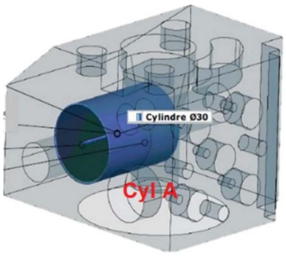
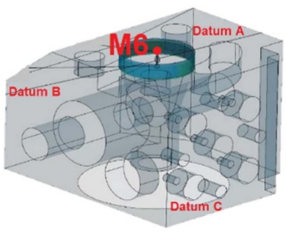
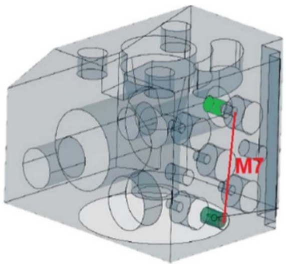
5. Calibration of the circulating part

The CAD Cube was calibrated, by Zeiss, with a tactile CMM Contura G2 using the measurement software Calypso 2021. An acquisition step of 0.1 mm was used, and 8071, 9661 and 5911 measurement points were performed on datum A, datum B and datum C respectively. Related to the first protocol, using maximum inscribed fit for the cylinders, 7 measurements, for reproducibility, were performed before circulation of the CAD Cube and 3 measurements were performed after circulation. When it was decided to push further the investigation on the measurement to adjust the XCT measurements to the reference (CMM) measurements, the CAD Cube was measured again three times implementing a second measurement protocol, using Gauss (least square) fit for the cylinders, except for M1 for which Chebyshev fit was used. The calibration measurements, implementing protocol 1 (before and after circulation of the CAD Cube) and protocol 2 (after circulation of the CAD Cube) for comparison, are provided in figure 5.

As expected, the cylindricity (M1) is similar for the two protocols (figure 5) as no change in the strategy has been made. The diameters (M2, M3 and M5) measured with protocol 2 are around 10 µm higher than those measured with protocol 1. This increase appears consistent with the change in strategy from maximum inscribed to Gaussian.

As the measurement uncertainty was not provided by Zeiss, the maximum permissible error (MPE) of the CMM was used instead: MPE $= [1.9 + L/300]$µm where L is given in mm. Thus, the referenced measurements ($x_{\mathrm{ass\_}p1}$ and $x_{\mathrm{ass\_p2}}$) as well as their associated uncertainty ($u_{\mathrm{ass\_p}1}$ and $u_{\mathrm{ass\_p2}}$) are given by:

Table 2. List and description of the measurands.

Measurand	Description	
M1	Cylindricity	
M2	Diameter	
M3	Diameter	
M4	Coaxiality cyl A versus cyl B	
M5	Diameter	
M6	Position in datum A versus datum B and datum C	
M7	Distance between the points at the intersections of the centre of the two cylinder axes with the plane for datum C	

For protocol 1:

$$x_{\mathrm{ass\_p1}} = \frac{\bar{x}_{\mathrm{CMM\_before\_p1}} + \bar{x}_{\mathrm{CMM\_after\_p1}}}{2} \tag{1}$$

$$u_{\mathrm{ass\_p1}} = \sqrt{\max^2\left(\mathrm{MPE}\left(\bar{x}_{\mathrm{CMM_{before_{p1}}}}\right), \mathrm{MPE}\left(\bar{x}_{\mathrm{CMM_{after_{p1}}}}\right)\right) + \left(\frac{\left|\bar{x}_{\mathrm{CMM\_before\_p1}} - \bar{x}_{\mathrm{CMM\_after\_p1}}\right|}{\sqrt{3}}\right)^2}. \tag{2}$$

For protocol 2:

$$x_{\mathrm{ass\_p2}} = \bar{x}_{\mathrm{CMM\_after\_p2}} \tag{3}$$

$$u_{\mathrm{ass\_p2}} = \mathrm{MPE}\left(x_{\mathrm{ass\_p2}}\right) \tag{4}$$

where p1 and p2 stand for protocol 1 and 2 respectively and $\bar{x}$ represents the average of the individual x measurements.

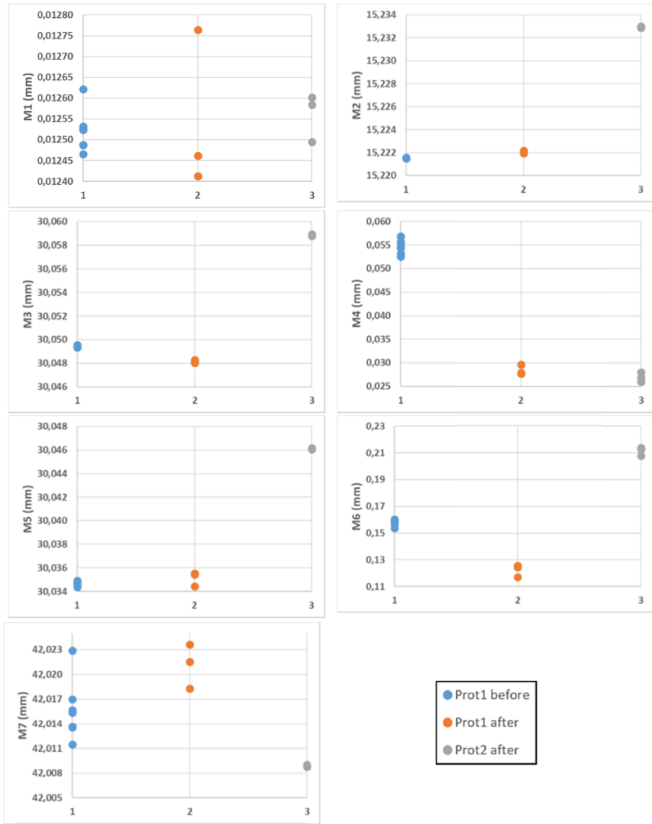


Figure 5. CMM calibration measurements of the CAD Cube implementing protocol 1 (before and after circulation of the CAD Cube) and protocol 2 (after circulation of the CAD Cube) for each measurand.

6. XCT measurements

6.1. Participants involved in the comparison campaign

The campaign involved seven French XCT users and system suppliers: 3D Casting, Baker Hughes, Cetim, Nikon Metrology, Safran Composites, Yxlon, and Zeiss but one of the participants performed the measurements with two different XCT sources, one microfocus but also one minifocus sources, thus the comparison campaign involved eight participants. As presented in table 3, six different XCT brands (Nikon, NSI, RX Solutions, Waygate Technologies, Yxlon, Zeiss) were used.

In order to preserve anonymity, each participant was designated by a number from 1 to 8 not related to the order in table 3.

6.2. XCT scans and 3D image reconstruction

A template table was sent to all participants beforehand, specifying the information to give on the XCT system, on the XCT scanning parameters and on the reconstruction and dimensional software used (Annex 2). It was asked to carry out three independent scans on the CAD Cube for repeatability. Thus, the object had to be removed from the XCT system in between each scan. A support holder, in polystyrene foam, was provided which tilted the CAD Cube in one direction (figure 6). It should be noted that participants 4 and 8 did not

Table 3. Participants and industrial XCT systems involved in the comparison campaign.

Participant name	XCT system used	
3D Casting	NSI X5000	
Baker Hughes	Waygate Technologies v|tome|x m 300	
Cetim	RX Solutions EasyTom 230	
Nikon Metrology	Nikon XTH225ST 2x	
Safran Composites	Waygate Technologies v|tome|x L 300 v|tome|x L450	
Yxlon	Yxlon FF35CT	
Zeiss	ZEISS METROTOM 1500 G3	

Figure 6. CAD Cube on the holder provided to perform the XCT scans.

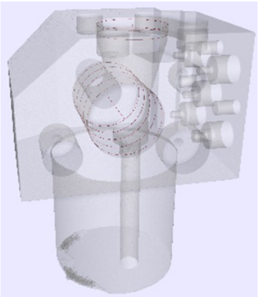


Figure 7. XCT image of the CAD Cube.

removed the CAD Cube from the XCT systems between each measurement and did not use the support. However no significant difference in terms of dispersion was observed on their measurements compared to the other participants, so their results were kept in the statistical analysis. As a result, the CAD Cube was not tilted during the scans for these two participants.

The participants were free to apply or not a beam hardening correction numerical filter on the reconstructed 3D image.

Figure 7 provides a 3D XCT image of the CAD Cube.

6.3. Dimensional measurements

The XCT dimensional measuring process includes the scans of the object, the 3D image reconstructions, the segmentation of this 3D images and then the dimensional measurements of the measurands with a dedicated software.

6.3.1. By each participant. The dimensional measurements performed by each participant on the 3D XCT images with their dedicated software, using protocols 1 and 3, are displayed in figures 8 and 9, respectively. All participants used VGSTUDIO Max except participant 7 who used GOM Volume Inspect. For comparison, the reference CMM measurements are also displayed as well as their expanded measurement uncertainty $U = 2\mathrm{xu}_{\mathrm{ass}}$.

With protocol 1, there is a high repeatability between participants with a few exceptions. The trueness seems to be better for position (M6) and distance (M7) measurements than for the other measurands (M1, M2, M3, M4, and M5). The dimensional measurements obtained implementing protocol 1 provide a significant bias between XCT and CMM measurements. This is mainly due to the fact that (1) the search distance was too small which filters a lot of real points from the analysis (in particular when the deviation between the numerical model and the scan surface part is important), (2) the safety distance was too small which can lead to bias due to points located at the edge of the cylinders or planes, points not considered in CMM measurements, and (3) the maximum inscribed strategy for the cylinders is too sensitive to marginal points (and therefore to artefacts).

Thus, at this stage of the comparison campaign, considering the gap between CMM and XCT measurements, protocol 1 was abandoned and it was decided to correct the measurement protocol in order to minimise this gap due mainly to an error in the measurement process defined in protocol 1. Thus, protocol 3 was elaborated.

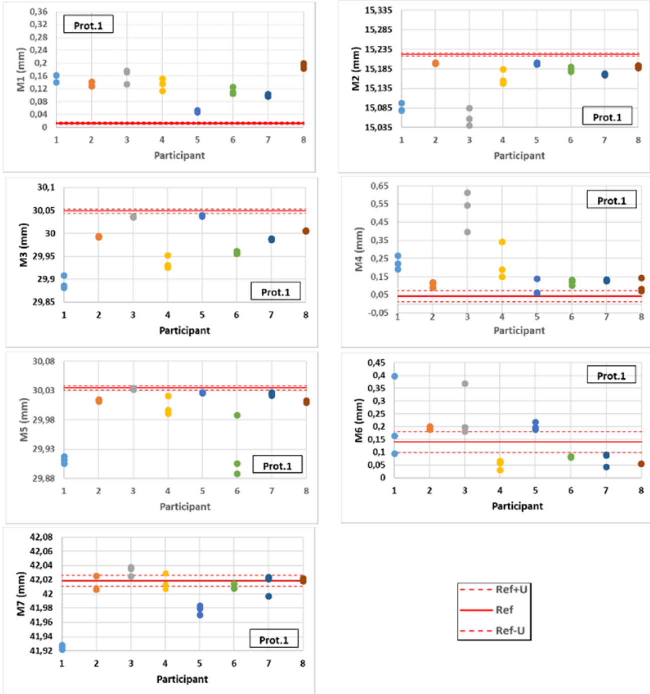


Figure 8. Comparison of XCT and CMM (Ref) measurements for each measurand and each participant: measurements performed by each participant using protocol 1.

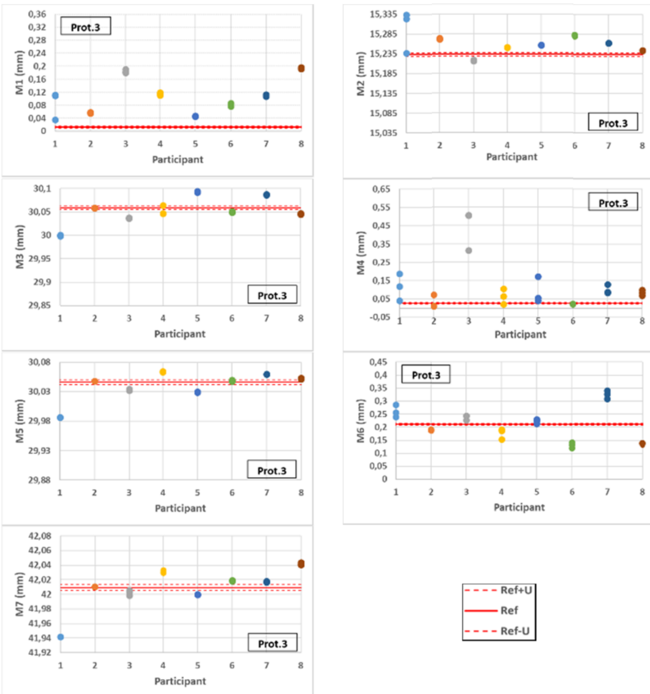


Figure 9. Comparison of XCT and CMM (Ref) measurements for each measurand and each participant : measurements performed by each participant using protocol 3.

The trueness is improved when considering protocol 3 for the diameters (M2, M3 and M5) as well as for the coaxiality (M4), position (M6) and distance (M7). Considering the cylindricity (M1), no real change in the measurement strategy

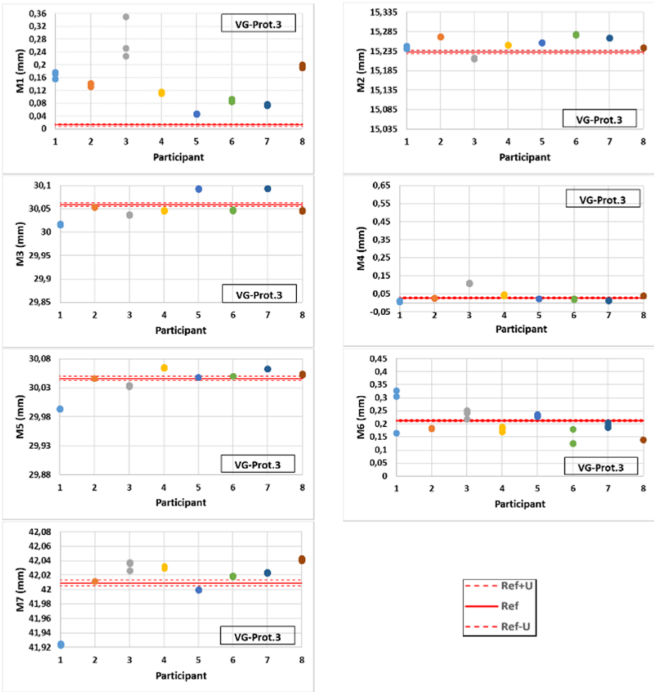


Figure 10. Comparison of XCT and CMM (Ref) measurements for each measurand and each participant: measurement performed by VG using protocol 3.

was made, Chebyshev method was implemented in both protocols 1 and 3. However, a volumetric Gaussian filter was applied in protocol 3 compare to protocol 1 and it seems that this filter has a slight influence. Indeed, a small improvement is observed with protocol 3 for most participants in term of dispersion or trueness.

6.3.2. By one operator with VG. The dimensional measurements performed by Volume Graphics with VGSTUDIO MAX version 2022.1 on the 3D XCT images provided by each participant, using protocol 3, are displayed in figure 10. For comparison, the reference CMM measurements are also displayed as well as their expanded measurement uncertainty U.

When the measurement process on the 3D image is made operator independent, the dispersion of the coaxiality measurement (M4) is improved and a non-uniform difference is observed for cylindricity (M1), otherwise the other measurands are not affected. Thus, one can conclude that the measurement process is only slightly affected by the operator for diameter, position and distance measurements.

6.3.3. By one operator with GOM Volume Inspect. The dimensional measurements performed by Zeiss with GOM Volume Inspect on the 3D XCT images provided by each participant, using protocols 2 and 3, are displayed in figures 11 and 12, respectively. For comparison, the reference CMM measurements are also displayed as well as their expanded

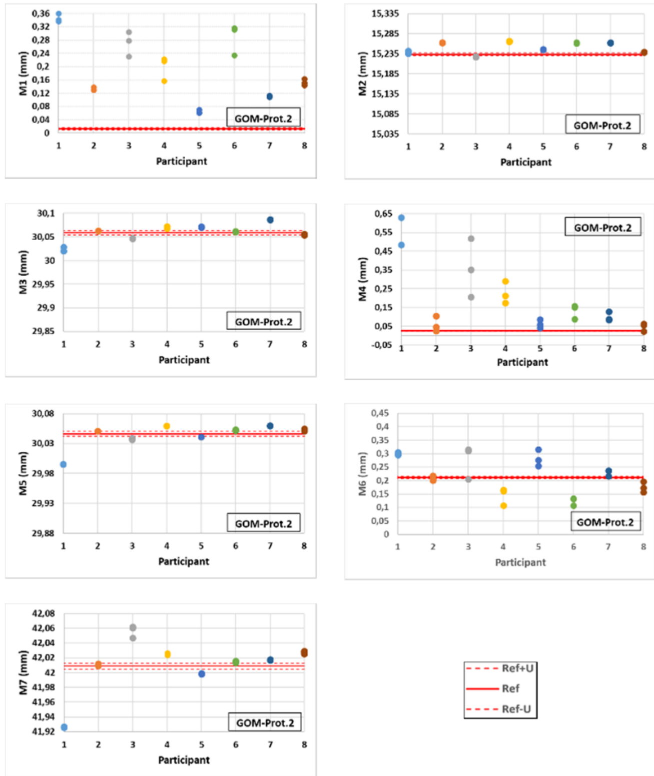


Figure 11. Comparison of XCT and CMM (Ref) measurements for each measurand and each participant: measurement performed by Zeiss using protocol 2.

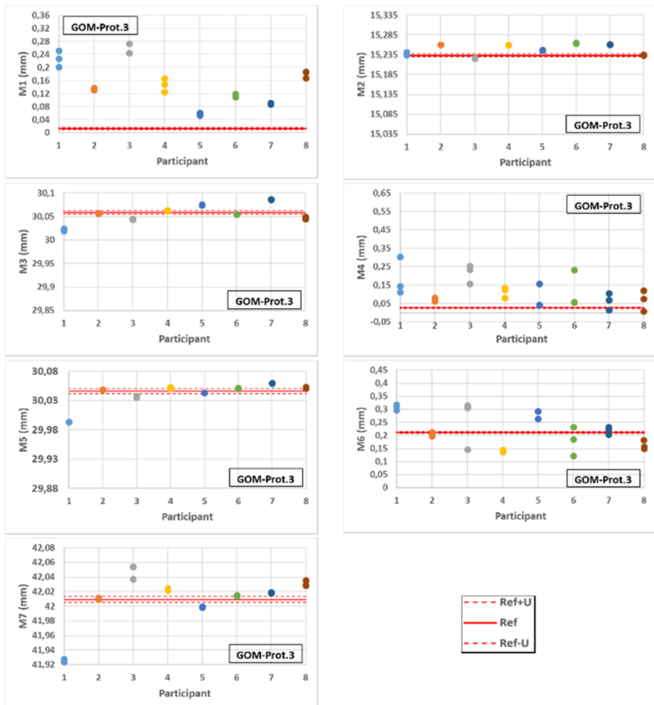


Figure 12. Comparison of XCT and CMM (Ref) measurements for each measurand and each participant: measurement performed by Zeiss using protocol 3.

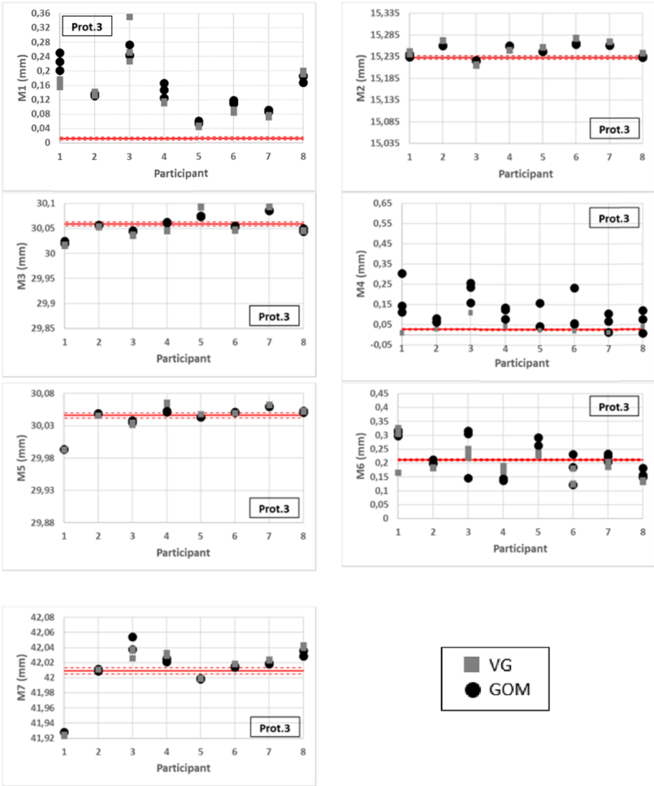


Figure 13. Comparison VG/GOM with protocol 3.

measurement uncertainty U. The protocol had to be slightly changed to process the data with GOM Volume Inspect to overcome some issues.

6.4. Measurement analysis

As can be observed from figures 9–12, there is a bias between XCT and CMM measurements with protocol 3 for cylindricity (M1) and coaxiality (M4) measurements except when measurements are performed by VG for M4. For the other measurands (diameters, position and distances), the bias are low.

In order to compare the effect of the software on the results, the measurements performed with GOM Volume Inspect and VGSTUDIO MAX were plotted on the same graph (figure 13).

In addition, in order to compare the effect of the volumetric Gaussian filter (reduction of the noise and artefact at the expense of the resolution) on the results, the measurements performed with protocols 2 and 3 were plotted on the same graph (figure 14).

As can be observed there is no influence of the software neither of the volumetric Gaussian filter on the diameter (M2, M3, and M5) and distance (M7) measurements. There is a high influence of both the software and the volumetric Gaussian filter on the coaxiality (M4) measurement, however the volumetric Gaussian filter allows to improve the measurements for few participants. There is an influence of the software and not of the volumetric Gaussian filter on position (M6) measurement. The opposite is observed for cylindricity (M1) measurement.

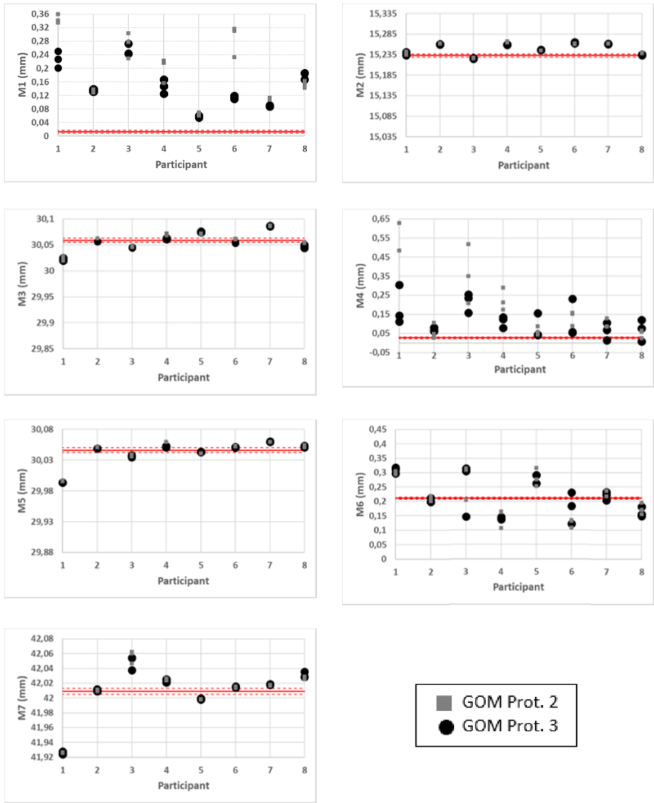


Figure 14. Comparison protocols 2/3 using GOM.

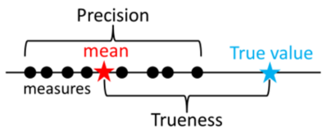


Figure 15. Schematic illustration of trueness and precision.

7. Comparison campaign statistical analysis

The results of the comparison campaign were analysed to evaluate the performance of XCT systems implementing ISO 5725-2 related to accuracy, and more specifically to one of the two components of accuracy: precision [5], and ISO 5725-4 related to the other component of accuracy: trueness [6] (figure 15).

The International vocabulary of metrology (VIM) [14] defined accuracy as 'closeness of agreement between a measured quantity value and a true quantity value of a measurand' and trueness (i.e. Bias) as 'closeness of agreement between the average of an infinite number of replicate measured quantity values ($Bias = \bar{x}_{lab} - x_{ass}$) and a reference quantity value (x_{ass})' such as.

$$\mathbf{Bias} = \bar{x}_{\mathrm{lab}} - x_{\mathrm{ass}}. \tag{5}$$

Precision is defined in the VIM [14] as 'closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions'.

Table 4. Eliminated participants (Part.) from the data analysis (outliers detected by the Cochran and Grubbs tests).

Eliminated participants	Number of participants	Participants	VG	GOM	
		Protocol 3	Protocol 3	Protocol 2	Protocol 3
Cochran test on variances	$p = 8$	M2 Part.1 M7 Part.1	M2 Part.1	M2 Part.1	M2 Part.1
Grubbs test on averages	$p = 8$	M5 Part.1 M7 Part.1	M5 Part.1 M7 Part.1	M5 Part.1 M7 Part.1	M5 Part.1 M7 Part.1

Table 5. Accuracy relative to measurements performed by each participant with protocol 3.

Prot. 3-Each participant	Measurandes	M1	M2 without lab1	M3	M5 without lab1	M4	M6	M7 without lab1
	$\bar{\bar{x}}_{\text{lab}}$ (mm)	0.109	15.255	30.053	30.048	0.119	0.210	42.017
Trueness	Bias (mm)	0.097	0.022	−0.006	0.002	0.092	−0.001	0.008
	Relative bias	7.715	0.001	$<10^{-3}$	$<10^{-3}$	3.405	−0.006	$<10^{-3}$
Precision	S_{r} (mm)	0.016	0.001	0.004	0.001	0.058	0.014	0.002
	S_{R} (mm)	0.056	0.021	0.029	0.013	0.143	0.067	0.015
Voxel/S_{R}		1.3	3.6	2.5	5.9	0.5	1.1	4.9

Table 6. Accuracy relative to measurements performed by VG with protocol 3.

Prot. 3-VG	Measurandes	M1	M2 without lab1	M3	M5 without lab1	M4	M6	M7 without lab1
	$\bar{\bar{x}}_{\text{lab}}$ (mm)	0.138	15.255	30.054	30.051	0.035	0.197	42.023
Trueness	Bias (mm)	0.125	0.022	−0.005	0.005	0.009	−0.015	0.014
	Relative bias	9.964	0.001	$<10^{-3}$	$<10^{-3}$	0.316	−0.070	$<10^{-3}$
Precision	S_{r} (mm)	0.024	0.001	0.001	0.001	0.002	0.034	0.003
	S_{R} (mm)	0.077	0.021	0.027	0.010	0.032	0.053	0.014
Voxel/S_{R}		1.0	3.5	2.8	7.1	2.3	1.4	5.2

Precision can be quantified by two uncertainty contributors, i.e. repeatability (S_{r}) and reproducibility (S_{R}). Repeatability represents the dispersion of the results obtained under unchanged measurement conditions. Whereas reproducibility represents the maximal dispersion due to the method (different laboratories, different instruments, different operators…).

The variances of the results were initially analysed with a Cochran test. If the test failed, the individual results associated to the maximum variance were analysed with a Grubbs test for the detection of outliers in the data set. After the outlier's removal if required (table 4), the repeatability S_{r} was evaluated as weighted mean of the standard deviation of each laboratory's results $S_{\text{r}i}$, according to:

$$\mathbf{S_r} = \left(\frac{1}{\sum \mathbf{dof}_i} \sum \mathbf{dof}_i \times \mathbf{S}_{\mathbf{r}i}^2\right)^{1/2} \tag{6}$$

where dof_i represents the number of degrees of freedom associated to the standard deviation $S_{\text{r}i}$. In addition, an ANOVA test (ANalysis Of VAriance) was performed on the participant's mean values to highlight systematic differences among laboratories. Measurement results affected by a systematic behaviour could be accounted for as laboratory effect S_{L}^2 evaluated according to:

$$\mathbf{S}_{\mathbf{L}}^2 = \mathbf{S}_d^2 - \mathbf{S}_{\mathbf{r}}^2 \tag{7}$$

where S_d^2 corresponds to n times the variance of the mean and n is the number of repeated measurements of each laboratory ($n = 3$ in this comparison campaign). Finally, the reproducibility standard deviation S_{R} was computed using:

$$\mathbf{S}_{\mathbf{R}}^2 = \mathbf{S}_{\mathbf{r}}^2 + \mathbf{S}_{\mathbf{L}}^2. \tag{8}$$

Furthermore, the results of the comparison campaign were also analysed implementing ISO 13528 [15] to evaluate the performance of each participant. The laboratory's capability to have results close to the reference value within its stated uncertainty can be assessed by a Z'score computed using:

$$\mathbf{Z'score} = \frac{\bar{\bar{\mathbf{x}}}_{\mathbf{lab}} - \mathbf{x}_{\mathbf{ass}}}{\sqrt{\mathbf{S}_{\mathbf{R}}^2 + \mathbf{u}_{\mathbf{ass}}^2}}. \tag{9}$$

The results of these different analysis are provided in tables 5–8 and the Z'scores in figures 16–19. In order to relate the reproducibility standard deviation to the voxel size (Voxel/S_{R}), the average of the voxel sizes over all laboratories was used.

One can observe different behaviours depending on the type of measurands. The diameter (M2, M3, and M5) measurements with XCT are reproducible, lower than 30 µm which corresponds to a subvoxelique factor of 2.5 and the trueness is less than 22 µm. The distance (M7) measurement with XCT is reproducible, lower than 15 µm which corresponds

Table 7. Accuracy relative to measurements performed by Zeiss with protocol 2.

Prot. 2-GOM	Measurandes	M1	M2 without lab1	M3	M5 without lab1	M4	M6	M7 without lab1
	$\bar{\bar{x}}_{\mathrm{lab}}$ (mm)	0.195	15.252	30.060	30.051	0.198	0.218	42.021
Trueness	Bias (mm)	0.182	0.019	0.001	0.005	0.172	0.006	0.013
	Relative bias	14.527	0.001	$<10^{-3}$	$<10^{-3}$	6.364	0.030	$<10^{-3}$
Precision	S_{r} (mm)	0.025	0.001	0.002	0.001	0.073	0.029	0.003
	S_{R} (mm)	0.100	0.015	0.019	0.008	0.202	0.070	0.018
	Voxel/S_{R}	0.7	5.0	3.9	8.9	0.4	1.1	4.0

Table 8. Accuracy relative to measurements performed by Zeiss with protocol 3.

	Measurandes	M1	M2 without lab1	M3	M5 without lab1	M4	M6	M7 without lab1
	$\bar{\bar{x}}_{\mathrm{lab}}$ (mm)	0.150	15.250	30.056	30.049	0.114	0.219	42.021
Trueness	Bias (mm)	0.138	0.017	−0.003	0.003	0.087	0.008	0.012
	Relative bias	10.960	0.001	$<10^{-3}$	$<10^{-3}$	3.225	0.038	$<10^{-3}$
Precision	S_{r} (mm)	0.014	0.001	0.001	0.001	0.065	0.040	0.004
	S_{R} (mm)	0.068	0.015	0.020	0.007	0.079	0.068	0.016
	Voxel/S_{R}	1.1	5.0	3.8	10.1	0.9	1.1	4.6

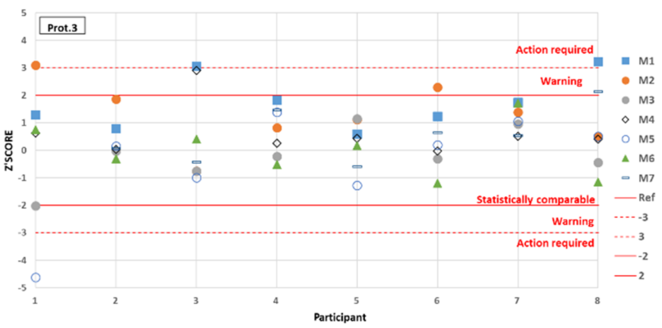


Figure 16. Z'scores relative to measurements performed by each participant with protocol 3.

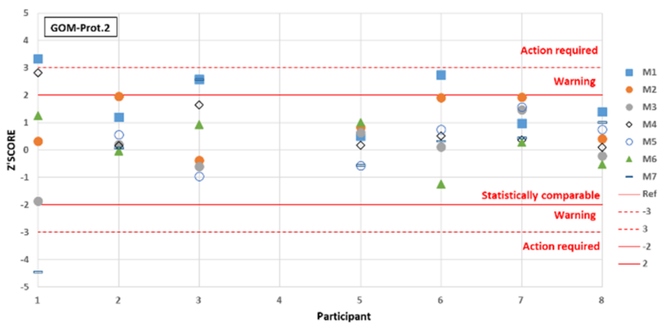


Figure 18. Z'scores relative to measurements performed by Zeiss with protocol 2.

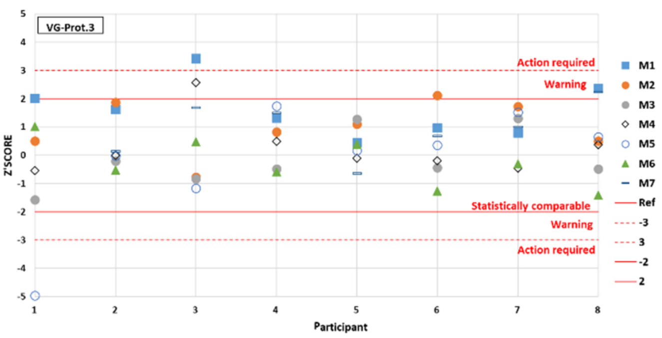


Figure 17. Z'scores relative to measurements performed by VG with protocol 3.

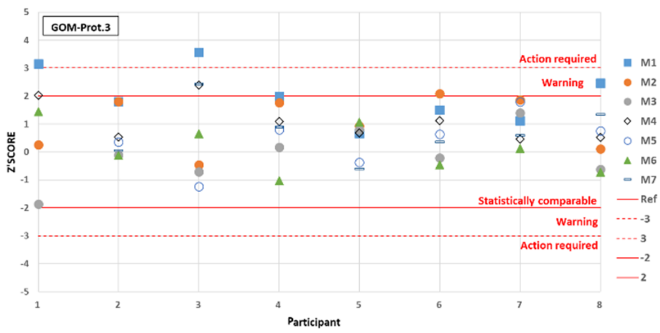


Figure 19. Z'scores relative to measurements performed by Zeiss with protocol 3.

to a subvoxelique factor of 4.9 and the trueness is no more than 8 µm. For these mesurands, their measurements do not depend on the used XCT system. However, the XCT measurements for cylindricity (M1), coaxiality (M4) and position (M6) are not reproducible, and their trueness deviates for the true value, except for the position which has a trueness lower than 1 µm. The process measurement should be revised regarding cylindricity and coaxiality measurements as the noise on the image generates variations on the measurements. An appropriate segmentation protocol should be defined. Thus, one can conclude that in this comparison, XCT encounters difficulties in measuring cylindricity and coaxiality.

Overall, considering the Z'scores, one can say that the capability of the participants to perform measurements with XCT, whatever their system, is statistically comparable.

Table 9. Summary of the influencing factors on dimensional measurements performed from XCT scans.

	Influencing factors		
Measurands	Operator	Measurement strategy	Volumetric Gaussian filter
Cylindricity (M1)	Medium	Medium	High
Diameter (M2, M3, M5)	Low	High	None
Coaxiality (M4)	High	High	High
Position (M6)	Low	High	Low
Distance (M7)	Low	Low	None

Differences < 5 µm ⇒ None, Differences < 25 µm ⇒ Low, 25 µm < difference < 50 µm ⇒ Medium, differences > 50 µm ⇒ High.

Table 10. Accuracy of dimensional measurements performed from XCT scans.

All participant, protocol 3	Trueness	Precision (reproducibility S_R)	Subvoxelique factor Voxel/S_R
Cylindricity (M1)	97 µm	56 µm	1.3
Diameter (M2, M3, M5)	<22 µm	<29 µm	>2.5
Coaxiality (M4)	92 µm	143 µm	0.5
Position (M6)	1 µm	67 µm	1.1
Distance (M7)	8 µm	15 µm	4.9

8. Conclusion

In this article, the results of an interlaboratory comparison campaign on XCT dimensional measurements have been presented. This campaign presented the particularity to involve an aluminium-machined object whose dimensions (92 × 78 × 63 mm^3) are significant for a 225 kV XCT system (regarding correlated penetration power for aluminium) and also larger than most of the other interlaboratory comparison campaigns. In addition, the campaign involved only height participants but a large panel of XCT system brands (Baker Hughes, Nikon, NSI, RX Solutions, Yxlon, Zeiss). Furthermore, two different measurement software (GOM Volume Inspect and VGSTUDIO MAX) were compared as well as three protocols which differences relied, one on the measurement strategy, and the other on the volumetric Gaussian filtering of the images.

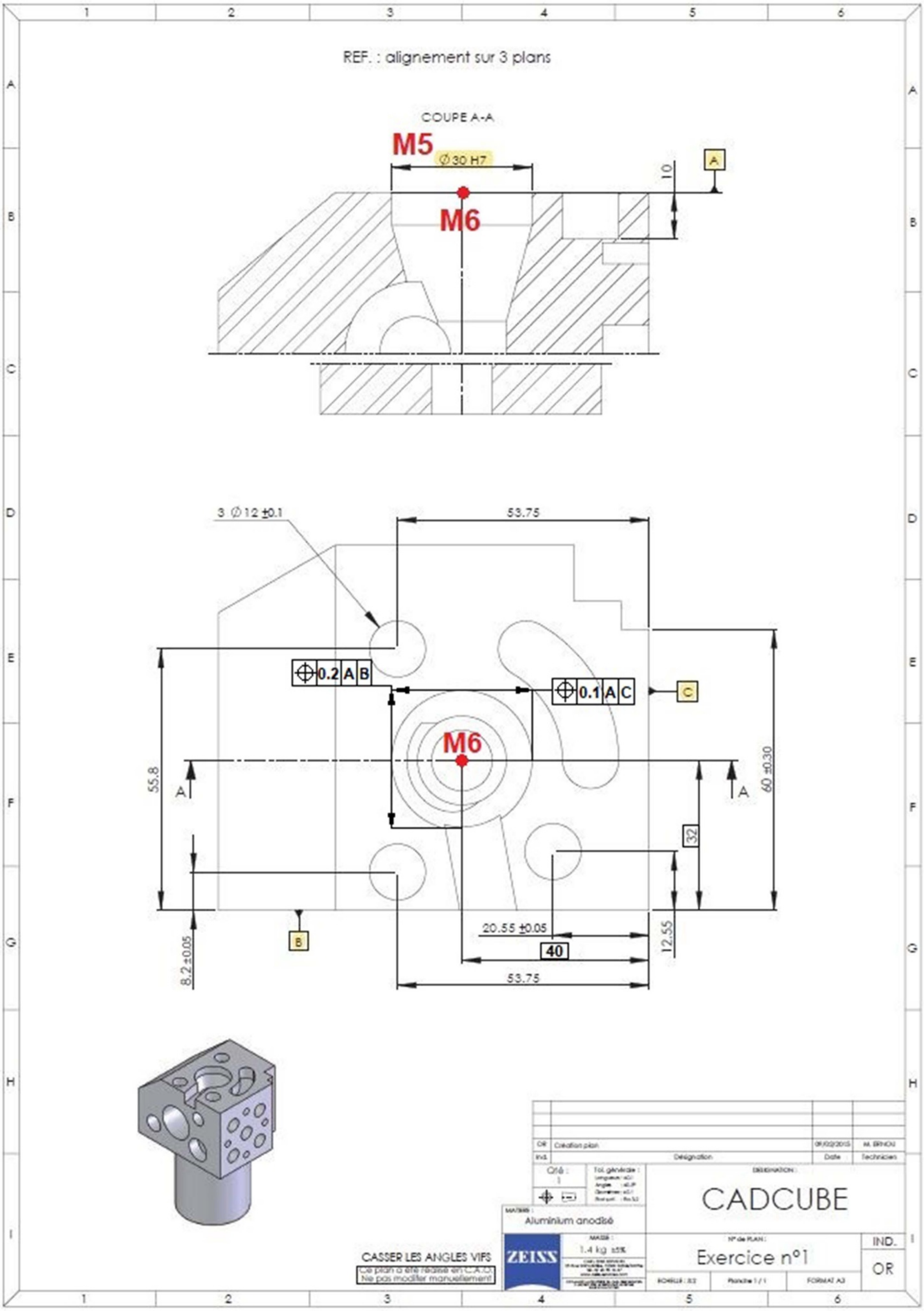
In this campaign, we have come to the conclusion (table 9) that the measurement process is affected by the operator only for cylindricity and coaxiality measurements, that there is no or limited influence of the software neither of the volumetric Gaussian filter on the diameter, and distance measurements. However, there is a medium to strong influence of the measurement strategy on all measurands, except distance, and there is an influence of both the software and volumetric Gaussian filter on the coaxiality measurement, whereas the volumetric Gaussian filter has a high influence on the cylindricity but not the software, which is the opposite for the position measurement. Furthermore, different behaviours, in terms of precision and trueness, are observed depending on the type of measurands when measured by each participant (table 10). The diameter measurements are reproducible with XCT, lower than 30 µm which corresponds to a subvoxelique factor of 2.5 and the trueness is lower than 22 µm. The distance measurement is also reproducible with XCT, 15 µm which corresponds to a subvoxelique factor of 4.9 and the trueness is 8 µm. For these mesurands, their measurements do not depend on the used XCT system. However, the XCT reproducibility for cylindricity, coaxiality and position is worse as well as the trueness except for the position which has a trueness of 1 µm. The measurement method should be revised regarding cylindricity and coaxiality measurements particularly affected by the noise on the image. Finally, the participants are statistically comparable, most of their Z'scores are lying inside the interval [−2, 2] except a few measurands.

This interlaboratory comparison campaign highlighted the following lessons learned : (a) the fact that three successive protocols have been required to optimize the results, is showing that dimensional measurement onto XCT volumes is complex regarding performances in terms of trueness (despite some specialists into our working group); (b) dimensional measurements onto XCT volumes is appearing as a complex process because it requires separate skills that are not yet commonly shared : on one hand, skills in XCT, on the other, skills in dimensional measurements; (c) nevertheless, with a proper and solid protocol (prot. 3 in our case), the comparison campaign shown that human factor can be put under control and rather equivalent results can be obtained whatever the measuring process (manual or batch processing), in terms of hardware (height XCT system's models and six brands) as well as measuring software (two brands); (d) current interlaboratory comparison campaign shall be considered as a starting point regarding needs that are currently incoming with AM parts where internal dimensions will be required (impossible with classical CMM); (e) last but not least, precautions shall be taken regarding the position (inclination) of the part to avoid or reduce geometric artefacts generated by 3D reconstruction.

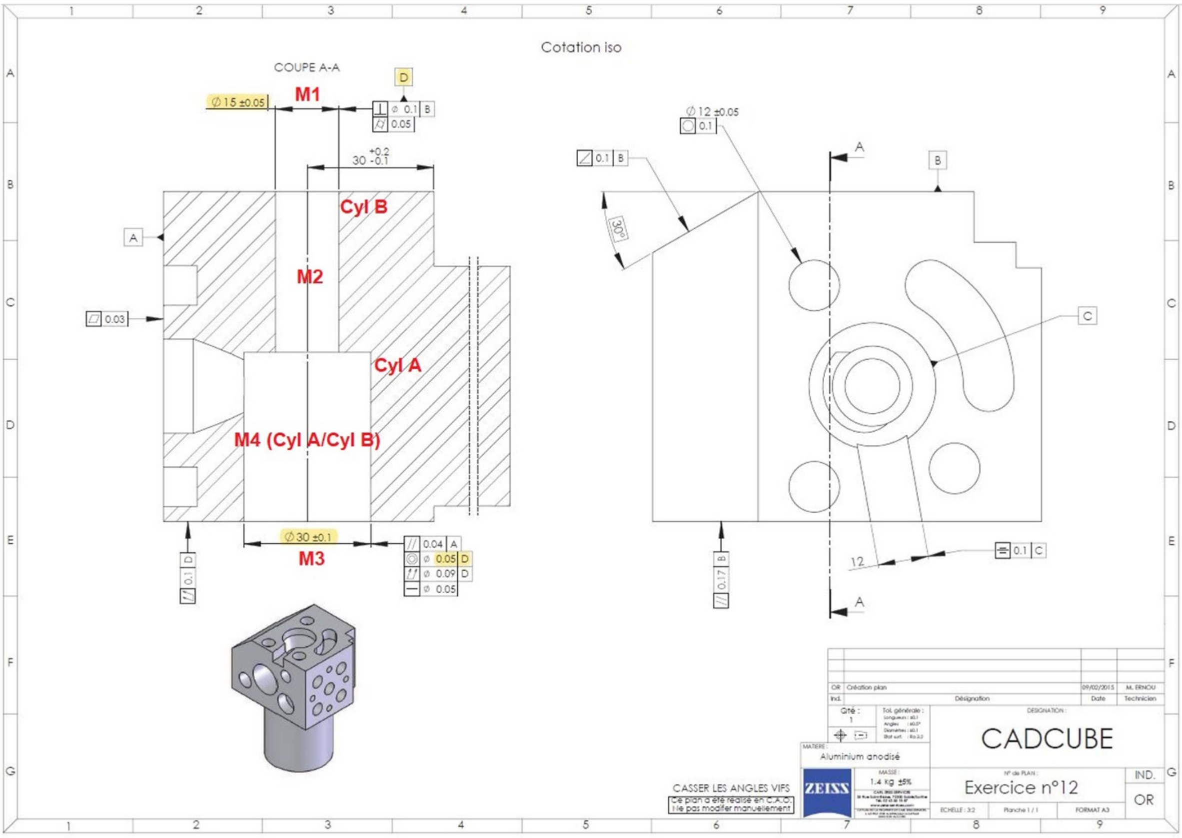
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix



Annex 1. Numerical design of the CAD Cube to illustrate the various measurands.



Annex 1. (Continued.)

Annex 2. XCT scanning parameters used by the participants depending of the XCT system.

Model	Focus spot type	Pitch size (µm)	Voltage (kV)	Current (µA)	Filter	Number of projection	Integration time (ms)	Number of image avg.	Voxel size (µm)
NSI X5000		200	215	120	1.5 Sn + 1.5 Cu	1440	1000	3	75
Waygate Technologies vltomelx m 300	micro	200	240	330	0.5 mm Cu	2200	334	3	85
RX Solutions EasyTom 230		127	225	376	1 mm Sn	2304	300	4	85
Nikon XTH225ST 2x		150	215	237	2 mm Cu	4476	500	4	55
Waygate Technologies vltomelx L 300		200	225	333	1 mm Cu	2000	131	10	70
Waygate Technologies vltomelx L450	Mini		450	1400	3 mm Cu			3	
Yxlon FF35CT	Micro	150	215	270	0.2 mm Cu	2700	1000	4	59
Zeiss Metrotom 1500 G3		139	220	534	1 mm Sn	3350	1000	1	83

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