4th Research/Expert Conference with International Participations
"QUALITY 2005", Fojnica, B&H, November 09-12, 2005.

CONCEPTUALIZATION OF COMPARATIVE MEASUREMENTS OF ARTEFACTS INTENDED FOR INSPECTION OF CMM LENGTH MEASURING CAPABILITY

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Keywords: CMM, inspection, length measurement test, material standard of size, artefact, comparison, positioning, measuring range

ABSTRACT

Inspection of CMMs length measurement capability is performed using various one-, two- or three-dimensional material standards of size (artefacts). Since there is no confirmation that CMMs length measurement tests conducted by some artefacts are more favourable, concerning reliability and significance of results, in relation to those conducted by some others, it seams to be reasonable to compare them in order to designate how different are statements about machines capabilities obtained thereby.

Artefacts comparison is a complex task and requires lot of attention in a planning phase. For example, general conditions under which the comparison measurements are to be conducted must be specified, suitable artefacts and machine/machines must be selected, geometrical and metrological features of the artefacts are to be designated etc. However, the most difficult tasks are to find a suitable positions of the artefacts during the measurements and to assure comparability of test results. In principle, it is necessary to analyse factors that could cause difference between results obtained by different artefacts and on the base of derived conclusions to develop a concept of positioning and measuring of the artefacts. At this, the concept needs to be compatible with possibilities of practical realisation of planned solutions and with recommendations from standards and guidelines.

This paper analyses the practicability of extensive analytical comparison tests of different 1D, 2D and 3D artefacts, dealing particularly with the planning of meaningful positioning of the artefacts in the measuring volume of the machine during the measurements and defining of solutions of results comparison.

1. INTRODUCTION

There are large number of procedures for CMMs performance verification. Generally, they are based on sampling the length measurement capability of a CMM. During that process it is checked whether the length measurement errors lay within the settled limits.

For the purpose of testing the capability of the machine to measure lengths with enough accuracy, two different concepts are recommended:

ISO 10360 - concept (accepted in VDI/VDE 2617 guidelines too): The tests are performed using different calibrated artefacts. Thereby test measurements determine errors (errors of indication of CMM at measuring lengths).

ASME B89.1.12M-1990 - concept: The results of test measurements are not errors, but range of the indicated results obtained by only one measurement length (volumetric tests). Thereby, use of calibrated artefacts is not required. "…the performance of the machine and its geometry is assessed, independent of conformance to international length standards [3]." Measurements on calibrated artefacts in this case need to be done only additionally, in order to provide traceability.

However, based on the one or on the other concept, the tests are performed using different length measurement standards (artefacts). The artefacts can be divided in accordance with arrangements of the measurement features (plane surfaces, cylinders or spheres) in the space, into **linear (one dimensional)**, **two dimensional** and **three dimensional**.

Usability of the artefacts is evaluated commonly by features such as efforts and outlay to be spent on measurements, amount of information provided thereby, calibration costs, transport possibilities, stability, handling, price etc.

However, there are different recommendations for artefacts selection and use, presented in the mentioned standards (ISO 10360, VDI/VDE 2617, ASME B89.1.12M-1990) or issued by different manufacturers. Thereby, those recommendations are not obligatory, and users have possibility to select and utilise the artefacts freely, especially for interim tests. It can, also, be noted that there are some trends (set by manufacturers) in recent time for recommending some of artefacts rather than some others (for example ball plates are recommended more frequently than hole plates) although plausible reasons for such trends are difficult to find.

Up to now, it is not known, at least it has not been published, how different statements about machines capabilities obtained by different artefacts are, and what are precisely, from metrological point of view advantages or disadvantages of certain artefacts. For example, it is only supposed that huge amount information provided by 2D artefacts, in comparison with several obtainable in the same time interval by the 1D artefacts, gives more comprehensive information about the state of machine. But, it is maybe sufficient to measure lengths in only several essential measuring lines, easy obtainable with 1D artefacts too, to gain a realistic information about machine capability to measure length.

Since there is no confirmation that CMMs length measurement tests conducted by some artefacts are more favourable, concerning reliability and significance of results, in relation to those conducted by some others, it seams to be reasonable to compare them in order to definitely designate how different are the statements about machines capabilities obtained thereby. Later, based on the comparison results one can conclude what causes eventual differences and point out artefacts features that are really favourable. Eventually, future trends concerning the development of the artefacts can be set.

Relevant artefacts that should be compared in one comprehensive comparison procedure include: gauge blocks, step gauge, hole bar, ball bar, ball plate, hole plate, hole cube, ball cube and ball tetrahedron [8]. Those artefacts are presented on the Figure 1.

Planning of the artefacts comparison includes determining many factors, for example, environmental conditions, measuring machine and its general characteristics (e.g. repeatability), probing system configurations and qualifications during measurements, dimensions of the artefacts and their calibration uncertainty, measurement strategies and operating conditions, solutions for mechanical alignment of artefacts in certain positions, required time etc. [8].

The planning phase of the artefacts comparison, namely its fundamental part, presents determining the comparison procedure. For that purpose, at first, suitable positions of the artefacts in a measuring range of a machine during the measurements must be generally determined. These positions must be defined in such a manner that comparability of test results is assured. In principle, it is necessary to analyse factors that could cause differences between results obtained by different artefacts and based on of derived conclusions to develop a concept of positioning and measuring of the artefacts. Additionally, the concept needs to be compatible with recommendations from standards and guidelines and with possibilities of practical realisation of planned solutions. In this conceptualisation, principal solutions for estimation of results must be included too. At least, the most significant problems that could appear at results comparison, must be recognised it order to point out a need to solve them in some future investigations.

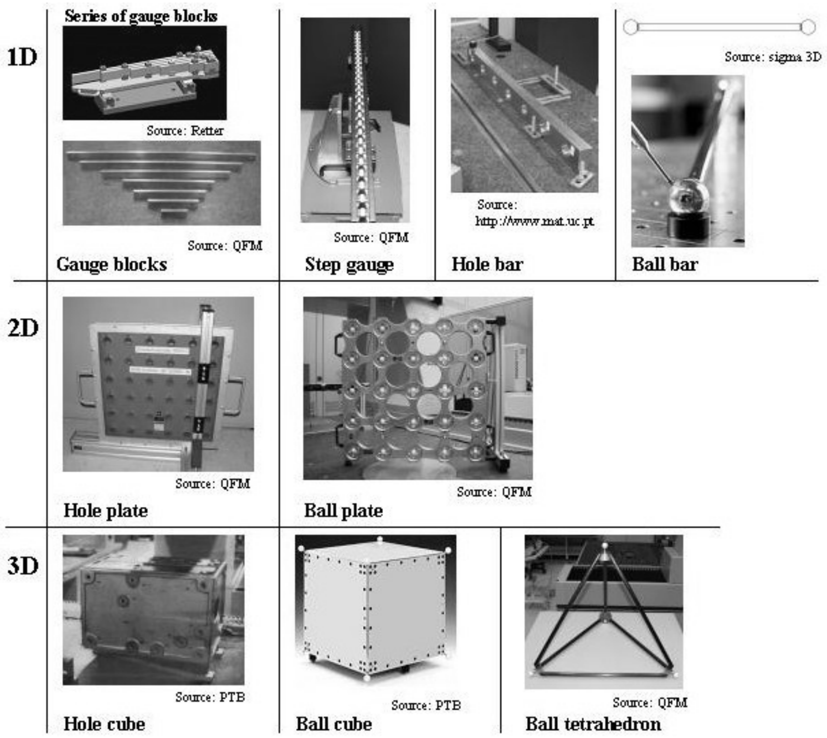

Figure 1. Artefacts Intended to be Compared

2. POSITIONS OF ARTEFACTS DURING THE MEASUREMENTS

2.1 What and why should be compared

In order to determine suitable positions of artefacts in the machine's measuring range during the measurements it is, at first, necessary to analyse possible reasons why the difference in test results between certain artefacts could appear.

If, for example, during the measurement the hole plate is arranged at an angle three-dimensionally, then probing parallel to the axes of the machine is not possible, so, probes need to be precisely oriented in accordance with orientation of the artefact, what is not always easy to obtain. If the cylinders have any form errors, this can cause the errors not caused by machine to be indicated.[5] Comparing such measurement with conditionally accurate results of measurement, obtained by some other artefacts, would certainly cause the differences in results to appear.

Necessity to compare certain artefacts is based on an analysis of reasons that can cause eventual differences in test results. Those reasons, set for different artefacts combinations, are presented in the Table 1.

Table 1. Reasons of Differences in Test Results that Could Appear at Comparison of Certain Artefacts

	Gauge blocks	**Step gauge**	**Hole bar**	**Ball bar**	**Hole plate**	**Ball plate**	**Hole cube**	**Ball cube**	**Ball-tetrahedr.**
Gauge blocks	√ Reasons: 1	-	-	-	-	-	-	-	-
Step gauge	√ Reasons: 2, 3, 4,	√ Reasons: 5	-	-	-	-	-	-	-
Hole bar	**X**	√ Reasons: 3, 6, 7, 13	√ Reasons: 1,	-	-	-	-	-	-
Ball bar	√ Reasons: 3, 8	√ Reasons: 3, 5, 7, 8, 9	√ Reasons: 6, 7, 9, 10	√ Reasons: 11	-	-	-	-	-
Hole plate	**X**	√ Reasons: 3, 6, 7, 12, 13	√ Reasons: 1, 7, 9, 11, 12	√ Reasons: 1, 6, 7, 9, 10, 12	√ Reasons: 1, 5	-	-	-	-
Ball plate	**X**	√ Reasons: 3, 7, 8, 12	√ Reasons: 6, 7, 10, 12	√ Reasons: 9, 11, 12	√ Reasons: 6, 7, 10	√ Reasons: 5	-	-	-
Hole cube	**X**	√ Reasons: 3, 5, 7	√ Reasons: 5, 7	√ Reasons: 5, 7, 9, 10	√ Reasons: 5, 6, 7, 12	√ Reasons: 5, 7, 10, 12	**X**	-	-
Ball cube	**X**	√ Reasons:3, 5, 7, 8, 9	√ Reasons: 5, 7, 9, 10	√ Reasons: 5, 11	√ Reasons: 5, 6, 7, 9, 10, 12	√ Reasons: 5, 9, 12	√ Reasons: 5, 7, 9, 10	√ Reasons: 5	-
Ball-tetrahed.	**X**	√ Reasons: 3, 5, 7, 8, 9	√ Reasons: 5, 6, 7, 9, 10	√ Reasons: 5, 11	√ Reasons: 5, 6, 7, 9, 10, 12	√ Reasons: 5, 9, 12	√ Reasons: 7, 9, 10, 14	√ Reasons: 5, 9	**X**

The reasons why differences in test results could appear/ effects that can cause differences/ motives for artefacts comparison:	
1	Different orientations of the artefacts on the same measuring line (rotated on the nominal measuring line in comparison to preliminary position for 90°, 180° or 270°)
2	Arrangement of the gauge blocks in the form of steps - measured lengths do not lay on one line as it is case with another 1D artefacts
3	Bi-directional probing of one artefact contrary to one-directional probing of the other artefact (not affected by the accuracy of qualification of probe diameter)
4	Different principles of alignment of the artefacts (although the alignment method used must be consistent with the procedures used during calibration)
5	Measuring lines obtained by placing the artefact in accordance with positions recommended in ISO 10360 and/or VDI 2617 contrary to results of additional measuring lines/positions
6	Three-dimensional positioning one or both artefacts - accessibility of measured features
(7)	Effect of shifting of the measured point (respectively obtained centre point) affected by deformed guide (axes) of machine [7]
8	Planar measuring features contrary to spherical measuring features (evaluation method, software influences)
9	Variety of measuring lengths of one artefacts contrary to single measuring length of the other artefact
10	Cylindrical measuring features contrary to spherical measuring features
11	Calibrated artefact used for length measuring test (in accordance with ISO 10360 and VDI/VDE 2617 procedures) contrary to "not calibrated" artefact used in combination with e.g. gauge block for providing a traceability (ASME B89.1.12M-1990 concept)
12	Variety of measuring lengths and/or lines differently oriented in the space, obtainable with one of the artefacts, contrary to only several measuring lines obtainable by checking CMM with another artefact (measuring in all recommended positions)
13	Planar measuring features contrary to cylindrical measuring features (evaluation method, software influences)
14	Different not standardized measuring lines

Keys:
√ - should be compared
X - there is no need to be compared

Statements in this table are not completely reliable. They can serve only for the purpose of the conceptualisation of artefacts positioning during planning of a comprehensive comparison. All possible reasons that could affect difference in results are not analysed here. For example, the axes could be sensitive to the load distribution and moment of inertia of the part being measured, consequently could load of the artefacts and moment of inertia of the artefacts affect the measurements [4], etc.

Comprehensive analysis of reasons that cause differences in test results will be made later in the phase of analysis of obtained test results.

Considering the reasons for difference in results presented in the Table 1, it is important to emphasise that, for the effect of shifting of measuring point (respectively, obtained centre point) affected by deformed guide (axes) of machine (the effect 7 in presented in the parenthesis), one has to check whether the indicated values are calculated by simple point-to point measurements or, by point-to point length measurements projected onto the alignment direction. In the second case this reason has no sense.

2.2 Positioning the artefacts in measuring range of a CMM during the measurements

Only from the data presented in the chapter 2.1, it can hardly be clear which positions are suitable for the measuring of the artefacts in order to obtain enough data for needs of comparisons. To plan them, positions and orientations of artefacts recommended by standards and guidelines could be taken as a starting point.

Generally, the standards and guidelines recommend as the most convenient, the following orientations of measuring lines: **paraxial** (parallel to the CMM axes, machine scales), **space-diagonal** and **coordinate plane-diagonal** (along certain plane diagonal).

VDI/VDE 2617, Part 2.1 (Code of practice for the application of DIN EN ISO 10360-2 for length measurement), 2005:

- 1D Artefacts (gauge block or step gauges) - in seven positions, across three measurement lines parallel to the coordinate axes and across the four body diagonals of the measuring volume. But, instead of arrangement of the measurement lines parallel to the three coordinate axes, it can be chosen the measurement lines 45° inclined and placed in the coordinate planes (coordinate plane-diagonal). Anywhere, each measurement line should be placed approximately in the centre of the measuring volume.

VDI/VDE 2617, Part 5 (Interim check with artefacts), 2001:

- 1D Artefacts (individual gauge blocks, series of gauge blocks or step gauge) - in at lest three positions across the body diagonals of the measuring volume.
- 2D Artefacts (ball plate, hole plate) - in at least two intersecting positions, in each position the measuring plane should be inclined to a coordinate plane 30° to 40°.
- 3D Artefacts (hole cube) - need to be measured in only one position.

VDI/VDE 2617, Part 5.1 (Interim check with ball plates), 2000:

- 2D Artefacts (ball plate) - vertically in the direction of a diagonal of the machine table (30° to 45° to one of the machine axes), or parallel to a plane spread between two machine axes (one horizontal and two vertical positions). The ball plate should be shifted into several positions in order to better cover the entire measuring volume of a measuring machine.

ISO 10360-2:2000:

- 1D Artefacts (series of gauge blocks, step gauge)
  Measurement sizes should be placed in seven different locations and/or orientations in the measuring volume of the CMM. The user is, of course, free to choose this locations and orientations. In the standard are not given any more precise suggestions. The extent of performance verifications during interim tests may be reduced by: number of measurements , location and orientations being performed.

ASME B89.1.12M-1990:

- 1D Artefacts
  - For linear displacement accuracy tests (step gauge): Measurement lines for step gauge tests shall be along three orthogonal lines through the centre of the work zone parallel to the three axis directions.

- For volumetric performance tests (ball bar): The general approach is to position the bar along 10 of 12 edges of the work zone, along at least six work zone face diagonals to require simultaneous motion of pairs of machine axes, and along the four work zone body diagonals to require simultaneous motion of all three machine axes.
- Ball bar test for offset probe performance: The ball bar should be measured in four positions. The user is free to choose any four positions within the machine volume, however, the default positions, which are most sensitive to ram axis angular motion are positions when the ball bar is 45° inclined to the ram axis.
- For bi-directional length measuring tests (gauge block): Three of four positions are roughly aligned with the machine axes, and the fourth is user selectable. It is recommended that this fourth position not be aligned with any machine axes. The exact location of the gauge block is not critical, however, it is recommended that this position be near the location in the work zone where the parts will most commonly be measured.

All described positions (measuring lines), presented in the cubic measuring range are given on the Figure 2. Also some additional positions for 1D and 2D artefacts are presented. Preliminary determined positions for 3D artefacts are presented on the Figure 3.

Generally, it can be accepted that in order to provide comparability and to obtain enough data for needs of comparisons, all artefacts should cover measuring lines described for 1D artefacts (Figure 2). So, for the artefacts for which positions recommended by the standards do not exist, suitable positions can be derived on the base of positions and measuring lines recommended for 1D artefact. Thereby, the practicability of positioning of the artefacts is important factor too (specially for the 3D artefacts). Also, the data from the chapter 2.1 are to be considered, but only as a base in a planning process, in order to provide all needed positions for measuring on the artefacts. From the derived concept, later, in the phase of concretisation of the general plan, after the dimensions of the artefacts are chosen, positions for concrete artefacts will be defined precisely and determined what will be compared in comparison of two certain artefacts. However, the concretisation of the comparison plan is not included within the scope of this paper.

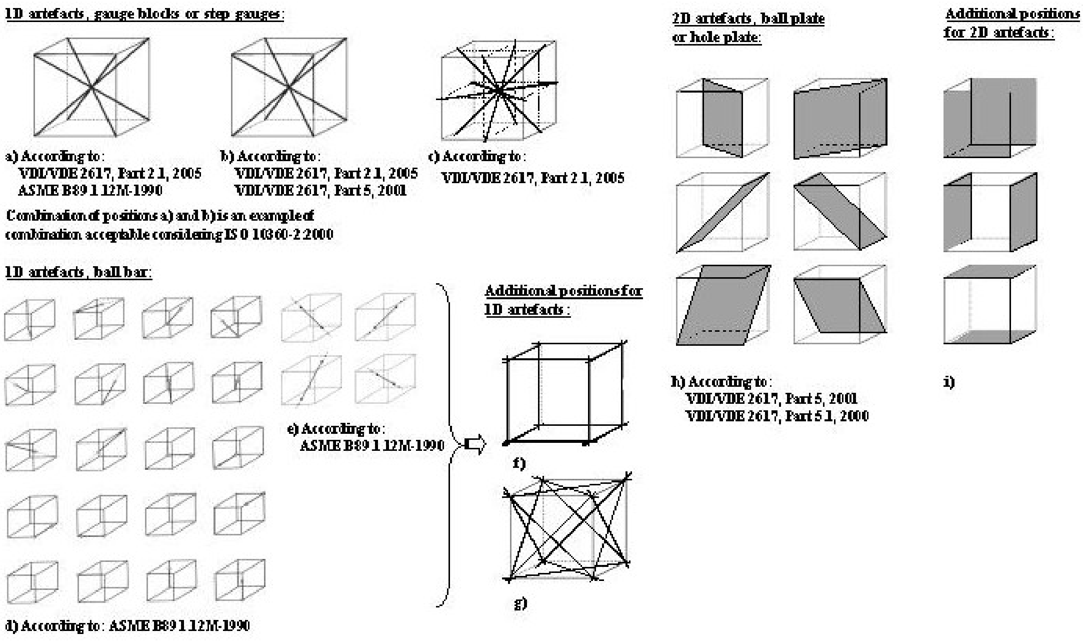

Figure 2. Orientations and Locations of 1D and 2D Artefacts in the Measuring Range of a CMM

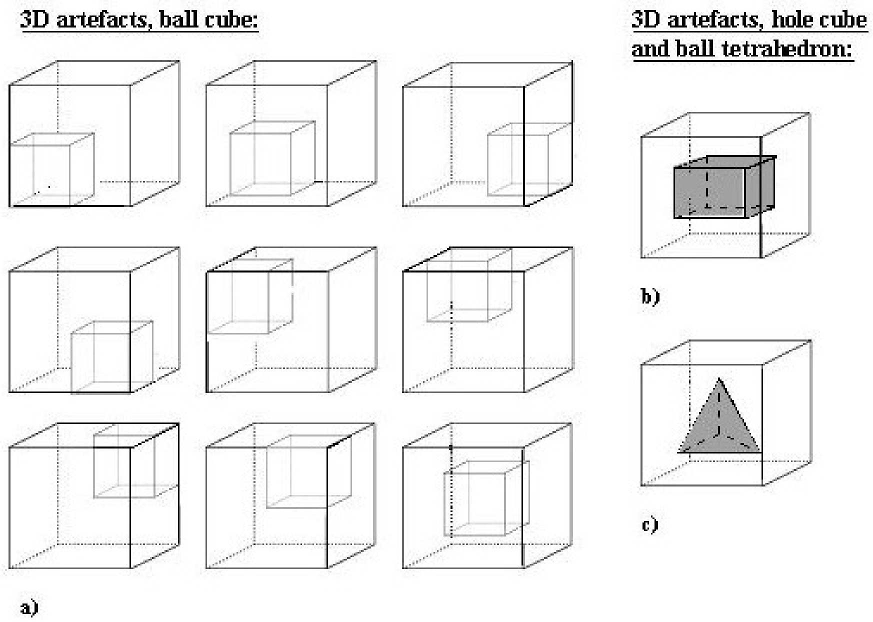

Figure 3. Orientations and Locations of 3D Artefacts in the Measuring Range of a CMM

3. COMPARABILITY OF TEST RESULTS

There are two important problems that can seriously influence comparison of test results and, there is no sense to continue planning artefacts comparison before suitable solutions for these problems are found:

- By means of variety of artefacts combinations it could be possible to research different influences of the artefacts on measurement results. Thereby, each effect that could cause differences, can be observed in different combinations with other influences.

However, if effects that cause differences are dependent on a physical shape of artefacts, or a number of measuring features, comparison of results is not a big problem. But, if effects are caused by a shape of measuring features, the evaluation becomes more difficult, or, in some cases, it is not possible at all. Thereby, the following solution can be helpful: The whole measurement range can be virtually divided in small sub-volumes. For example, the space of $1m^3$ (10^9 mm^3) can be divided on 125 000 parts with dimensions $8 \cdot 10^3$ mm^3 (20 mm x 20 mm x 20 mm). In that grid, every measured distance will be determined with additional information about location of the measuring line. That means, sub-volumes of two points that make certain measuring length, will be known. Thus, corresponding lengths, lengths whose two determination points lay in the same small sub-volumes, can be directly compared.

- Another problem of the results comparison is a problem of the different uncertainties of artefacts calibrations. If obtained results are compared in the relation with MPE (maximal permissible errors of indication) limits, than it could be reasonable to increase recommended limits, for a value of a bigger calibration uncertainty of two artefacts. But, in the case of direct comparison of measuring results of the same lengths, whose determination points are placed in the same sub-volumes, calibration uncertainty of the artefacts could be very problematic factor. In this case, measurement errors, instead of two lengths, would be compared (otherwise, the important role would not play calibration uncertainties of the artefacts but only an actual measuring uncertainty). So, if the difference of results is bigger as a sum of both calibration uncertainties, than it is sure that the difference really exists - in other case, the difference is questionable. However, from this analysis it is clear that next researches in field of planning of the artefacts comparison should deal with this problem, since it seems to be critical for applicability of artefacts comparison.

4. CONCLUSION

For the purpose of conceptualisation of the artefacts comparison, the most important is to plan:

- suitable measuring positions of the artefacts in the measuring range of the machine and,
- possibilities for comparison of obtained results considering the most important problems that could appear at that.

For the purpose of the determination of positions in which the artefacts should be measured, it is important to analyse reasons that could cause differences in results. Thereby, there is a total of 37 different combinations of artefacts to be considered. Based on results of such analysis and data from the relevant standards and guidelines, generally the following rule could be accepted: All artefacts should be positioned in such a manner to cover measuring lines determined for 1D artefacts (positions recommended in the ISO 10360, VDI/VDE 2617 and ASME B89.1.12M-1990). Thereby, regarding the practicability of positioning, their individuality in design and disposition of the measuring features, it is allowed for some 3D artefacts to be measured in only one position - in the centre of the measuring volume (hole cube and ball tetrahedron).

From the derived concept, later, in the phase of the concretisation of the general plan, positions for concrete artefacts can be defined precisely and, for each two certain artefacts, can be determined what exactly will be compared.

Regarding the principal solutions for estimation of results, it is suggested to divide virtually the whole measurement volume in small sub-volumes of dimensions 20 mm x 20 mm x 20 mm. Thus, two corresponding lengths, whose determination points lay in the same small sub-volumes, can be compared directly.

As the most significant problem to provide comparability of test results is recognised a problem of the different uncertainties of artefacts calibrations. This problem should be taken in consideration in future investigations of the artefacts comparison possibilities.

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