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Towards a Definition of "Geometric Verification Specifications" Within the ISO GPS System

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Abstract

The primary scope of tolerancing is to ensure functional requirements will be met by specifying geometrical tolerances. The duality principle, described within the ISO Geometrical Product Specification (GPS) standards, presents a perspective where the verification conceptually mirrors the specification. While this is a valuable model, further refinement is required to accommodate the different aims of inspection in support of the manufacturing process. This work aims to elaborate on the concept of a "geometrical verification specification" that is subordinate to the functional and/or manufacturing specifications. This verification specification may evolve as additional knowledge of the manufacturing process and inspection resources becomes available. A well-formed geometric verification specification should facilitate an appropriate inspection by any qualified operator, which in turn assures comparable measurement results across multiple instruments and facilities.

Keywords: Geometric Specififcation; ISO/TS 21619:2018; Design for Metrology

1. Introduction

The primary scope of the tolerancing activity is to ensure functional requirements will be met through the specification of geometrical tolerances [1,2]. During the design phase, the *geometric functional specification* is created by the designer translating functional requirements (i.e., performance) into geometric specifications (i.e., tolerances). This *geometric functional specification* addresses the part in its "as assembled" state as part of the final product [3].

Manufacturing processes are defined in terms of tools, steps, and requirements; it is for these processes that *geometric manufacturing specification* documents are generated. The focus is no longer directly on functionality, but on the quantities directly controlled by the manufacturing process. As the knowledge of the manufacturing process increases, the *geometric manufacturing specification* may be updated accordingly, allowing the tightening or relaxing of tolerances where possible and/or convenient.

1.1. Specification vs. verification

The duality principle, described within the ISO Geometrical Product Specification (GPS) standards [4], presents a perspective where the verification conceptually mirrors the specification. While this is a valuable model, further refinement is required to accommodate the different aims of inspection as the manufacturing process evolves. If one were to infer that the duality principle ideally implies a one-to-one correspondence between specification and verification, then the creation of the *geometric functional specification* and *geometric manufacturing specification* would imply only two unique verifications exist. However, inspections are performed with different aims for both functional and manufacturing

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purposes during the product development cycle, and a means of differentiating verification strategies is needed.

This observation underscores the need for geometric inspection-oriented information that may be captured unambiguously. The work reported here aims to elaborate on the definition of a *geometric verification specification* exploring its usage in the product development lifecycle for the reasons explained in subsection 1.2.

1.2. Geometric verification specification

ISO/TS 21619 [5] defines the *verification specification* as a "document stating verification-process-related requirements" that is derived from, and dependent on, higher-level specifications (i.e., functional and manufacturing specifications) through a process of transformation. This technical specification does not suggest how this transformation takes place or how the resulting documents are used.

There is limited literature providing insights regarding "verification specifications" in the domain of mechanical assemblies and parts. It is worth noting the statement by Woo that carefully created verification specifications allow for avoiding divergence from the designated procedure and/or aim over time [6].

NASA's System Engineering Handbook points out a list of 18 items that are conveyed in the verification procedure and 11 items that shall be present in the verification report [7]. Even though this work is not related to mechanical assemblies it is worth noting that items in the verification procedure (e.g., calibrations intervals, data recording procedures, measuring equipment, single operations sequence, etc.) contribute to an understanding of the overall verification procedure uncertainty.

The hierarchy of specifications requires that the *geometric verification specification* be subordinate to the *geometric functional and/or manufacturing specifications*. One important part of the *geometric verification specification* is the management of verification uncertainty. If any qualified operator performs the inspection by strictly adhering to this specification, the estimated (budgeted) measurement uncertainty should be met and comparable measurement results across multiple instruments and facilities should be achieved.

The *geometric verification specification* is not intended to be a static document throughout the development cycle. The main reasons for the evolution of the specification are the increasing knowledge of the manufacturing process and the changes in resource availability.

In the following section different geometric verification purposes will be analyzed, highlighting the specificities that lead to different versions of a *geometric verification specification*. Next, the specific information needed in a verification specification will be presented and discussed. Finally, a case study will be presented.

2. Verification purpose

The metrological inspection of mechanical parts has two main objectives: the determination of conformity to a GPS specification and the support of the manufacturing process. These two objectives can be further subdivided based on the character of the information needed from the inspection. For instance, a geometric functional inspection can be performed for supplier qualification, inbound batch approval, selective assembly, etc. while a geometric manufacturing inspection could be used for process tuning, statistical process control (SPC), in-line checks, etc. These applications are briefly discussed in the following subsections.

2.1. Supplier qualification

Supplier qualification provides confidence that a supplier can provide a functional part. The customer's interest is in the functionality and should not be interested in the manufacturing process, leading to a functionally based inspection. Usually, 30 to 50 parts are considered and all of the tolerances in the geometric functional specification are checked. Since this type of inspection is performed at the beginning of production for a limited number of parts, there is almost no time constraint. Consequently, this type of check is the closest to the direct application of the duality principle to the *geometric functional specification*. Nonetheless, valuable information can be added to drive the verification procedure, as discussed in section 3.

2.2. Inbound batch approval

A customer may be interested in checking whether subsequent incoming batches are within geometrical functional limits even if the supplier was qualified. The batch approval may be held to a specific timeframe set by the warehouse schedule. For this reason, the speed of the inspection is essential and a trade-off among different possibilities is necessary. For instance, a small sample may be fully checked according to the geometric functional specification; a larger sample may be checked only for pre-defined Critical to Quality (CTQ) tolerances or by using functional gauges (go/no-go test).

2.3. Selective assembly

Selective assembly is a strategy used when the manufacturing process is not capable of producing parts that guarantee interchangeable assembly [8]. Inspection can be used to cluster the parts in different groups based on a critical assembly characteristic; each class can then be paired with a specific class of the mating part ensuring interchangeability within the paired classes. Since functionality is addressed in this case, it is certainly a geometric functional inspection, albeit different from the previously described ones. Traceability between the measurement and the actual feature (measurand) is needed: agreed-upon binning or marking needs to be prescribed to track the parts.

2.4. Manufacturing/assembly process tuning

Manufacturing processes initially need to be calibrated to find appropriate process parameters to achieve the expected geometric quality. Simulation is a viable tool to define the preliminary process parameters, but the ground truth can be seen only in the produced parts. Consequently, parts need to be inspected based on the *geometric manufacturing specification* assessing the actual performance of the process. The measurands associated with this type of geometric inspection need to be consistent with the quantity controlled by the manufacturing process. If the location of a cylindrical Feature of Size (FoS) is only reported by the minimum tolerance zone containing the non-ideal feature [9,10], then any directional information allowing for process tuning is missing. Therefore, the directional quantities to be extracted from the location tolerance need to be defined, paying particular attention to the coordinate reference system to avoid ambiguity regarding the direction of the deviations.

2.5. Statistical process control

The aim of SPC is to evaluate whether the manufacturing process remains stable with only chance deviations. Depending on the details of the manufacturing process, a certain level of covariance among similar "critical to quality" tolerances can be expected during production. In this case, verifying all the dimensions gives redundant information. A subset of the tolerances can be chosen for SPC, reducing inspection time. Knowledge of the manufacturing process is used to refine the specification so that key performance tolerances can be defined and/or updated. As with process tuning, directionality can play an important role in the inspection and the same considerations from the previous section apply.

Work by Zang and Lu [11] reported on standardization in China of quality-oriented statistical tolerancing where tolerances are assigned to a population of parts. There have been efforts in this field [12] for the life of the ISO GPS system, but the results in both standards and practice are still difficult to generalize.

2.6. In-line checks

In-line checks are essential for safety-critical applications and/or when the economic risk of allowing nonfunctional parts in the production line is high; therefore, 100% of the production is inspected. The check is performed at either of two points: the exit of a manufacturing step (manufacturing inspection) or entering the assembly line (functional inspection). In both cases, the time needed to perform the inspection is critical and results must be obtained at the pace of the production line. Careful attention is needed in the definition of the inspected quantities, allowing reproducible inspection across different production sites. Previous research developed a methodology to assess the economic impact of metrology in manufacturing, giving a tool to identify economically sound inspections [13].

3. Contents of the verification specification

To drive the different geometric verification procedures, the *geometric verification specification* needs a sufficient set of information to support the corresponding "parent" specifications and to decrease the ambiguity in the inspection procedure.

Before initiating the inspection process, the first task is the identification of each specification (i.e., ballooning) which assigns an ID to each tolerance. Different personnel may follow different strategies to assign the IDs, so it is preferable that a unique identifier be assigned at the specification stage. This could be achieved on the drawing with a number between angle brackets (i.e., <#>); members of ISO TC213 are discussing the possibility of standardizing this technique. Patterns of features may have a single call-out assigning the same tolerance to each feature; these must be identified as separate tolerances for each feature for analysis and reporting.

The next step in inspection planning is the association of each tolerance to the proper metrological equipment. To ensure that measurements made in different plants can be directly compared, the same measurands should have comparable expanded uncertainties. An uncertainty requirement shall be added (based on the case) containing a: statement of the target uncertainty (U_T) as described in ISO 14253-2 [14], requirement that each quantity shall be reported with its expanded uncertainty or conformity will be determined using a specified decision rule and/or acceptable risk for each tolerance [15,16].

As there is no direct translation from a datum reference frame to a cartesian coordinate system, the explicit indication of the coordinate system allows the identification of the correct information for process tuning, and avoids misinterpretations.

During the actual inspection many contributors to uncertainty are present, some of which can be managed through a dedicated geometric specification. ISO 14253-2:2011 reviews and describes ten categories of uncertainty: *environment*, *reference element of measurement equipment*, *measurement equipment*, *measurement setup*, *software and calculations*, *metrologist*, *measuring object*, the *definition of the characteristic*, *measuring procedure*, and *physical constant* [14]. Some of these are addressed below, with commentary regarding the management of their impact using the *geometric verification specification*.

For dimensional inspection, the thermal *environment* is the most significant contributor (20 °C per ISO 1:2016) although other environmental variables such as humidity, illumination, thermal equilibrium, and time/spatial gradients of variables are also important. In particular, in-line inspections may need a statement of environmental conditions.

S*oftware and calculation* are often anathema to standard practice. Modern metrology software has such a vast array of options that collecting all the settings that can be applied during measurement may be impossible. Two of the most important parameters are the choice of filters and association criteria. These have a strong impact on the geometric inferences drawn from raw measurement points and should be specified based on the manufacturing process, inspection equipment, and intended output of the geometric verification. The designer may have limited information about manufacturing and inspection but should be consulted to ensure that the functional requirements are adequately captured by these choices.

The selection and use of *measuring equipment* are intentionally omitted from geometric product specifications, separating verification from the specified geometry. While traceability is required for most industrial measurements, the means of attaining it is not.

The specifics regarding *measuring set-up* (i.e., how the measuring equipment is used) cannot be completely captured geometrically. Nonetheless, it may be useful to suggest a measuring set-up (possibly in a separate document) to allow a different plant with similar equipment to mirror the set-up or for an experienced metrologist to adapt the set-up to a different piece of equipment.

The importance of the *measurement object* (i.e., how the measuring equipment and set-up interact with the object) is reflected in two ways. Firstly, the workpiece has geometric deviations (based on the manufacturing process) that will interact with choices made about measurement, and secondly, the workpiece is not perfectly rigid – despite the implied assumption of rigidity in the functional specification. For instance, it may be useful to state the direction of gravity in the verification specification and the part placement in the measuring system.

A relevant contributor to the measurement uncertainty is the *measuring procedure*; the same equipment used in the same environmental conditions can produce very different measured values if different procedures are followed. A comprehensive description of the measuring procedure will include points already discussed in this list. In addition, other requirements such as the order or measurements and the number of sampled points can appear in a separate document.

Finally, the *metrologist* themselves contributes to the overall uncertainty, often when making choices regarding the items discussed above. The metrologist remains the free variable in the whole idea of the geometric verification specification.

4. Case study

To show the applicability and the usefulness of a dedicated *geometric verification specification* the concepts explained above have been implemented in a case study. The example consists of a simple spacer with eight through-holes. From a functional point of view, the spacer needs to establish a distance between two mating parts and eight pins need to pass through without interference. A geometric functional specification, consistent with this functional description, is presented in Figure 2. The median plane of the mating surfaces is the primary datum, and the pattern becomes the secondary datum, therefore defining a symmetric datum system in accordance with the four possible mounting positions. This type of drawing allows for describing the pure functionality in the cleanest way possible; no unnecessary tolerances and indications are added.

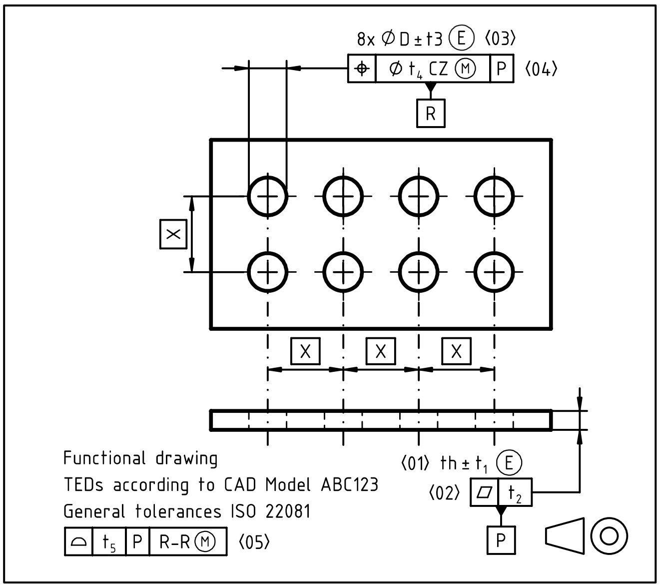

Figure 2: Geometric functional specification for the case study.

Let us assume that the most severe assembly risk is caused by errors in the pattern of through holes. Misalignment of the pins through the holes must be avoided to prevent damaging the mating parts during assembly. The thickness check is less critical since the spacer can be replaced without damage if its thickness is out of specification. Based on these assumptions about criticality, each spacer will be subjected to an in-line check entering the assembly process; a geometric verification specification for this check is now created. As the hole pattern is primarily two-dimensional, the inspection is performed with an optical system: the part is positioned on the measuring platform and the holes are sampled through image recognition. The pattern is then compared to the virtual condition to ensure assembleability.

Figure 1 shows a possible verification geometric specification for this purpose; the primary datum is assigned to

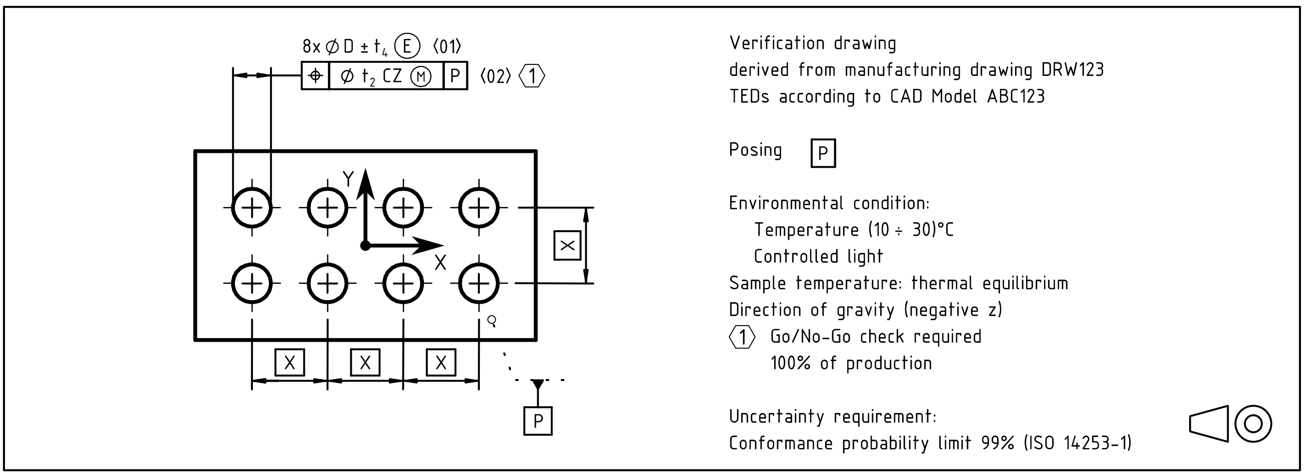

Figure 1: Geometric verification specification dedicated to in-line functional check.

the bottom surface and the pattern is checked in dimension and position. The primary datum is not checked directly, but reflects the placement of the part on the measuring device. Given the measuring principle, the 2D holes sampling already integrates 3D deviation effects to the virtual condition.

Other data included in this verification specification are: parent functional specification, part posing, environmental conditions, part temperature range, type of assessment (go/no-go check), and a decision rule statement. Since it is an optical inspection, the requirement of constant light conditions is added. Being an inline check, the ambient temperature cannot be controlled precisely, the limits are established to comply with the uncertainty statement. If the check needs to be reproduced in a second plant and/or the equipment needs to be updated, this type of specification clarifies exactly the requirements that need to be respected.

Moving upstream to the manufacturing process, we assume the part is produced by a CNC milling machine. A possible geometric manufacturing specification is shown in Figure 3. Here the datum system reflects the fixturing in the milling machine, removing the symmetry of the specification. Care must be used when changing the location of a pattern form a self-defined reference system to an external one [17].

The manufacturing drawing targets the production process, which guides the geometric verification specification in a way that can provide tuning and feedback to this process; the result can be seen in Figure 4. As it is assumed that the geometry is produced by a combination of milling and drilling, the quantities more likely to exhibit errors are the hole positions in the plane; the orientation errors are likely to be negligible.

The alignment marking for orientation and the specific naming for each item in the pattern to establish traceability are added. The posing, Figure 5, is described using the datum symbols even if they do not belong to the manufacturing datum system. The use of movable datum targets allows a detailed description of the posing itself. One feature is part of both datum systems but is identified with two names since for the manufacturing datum system it is considered as integral feature

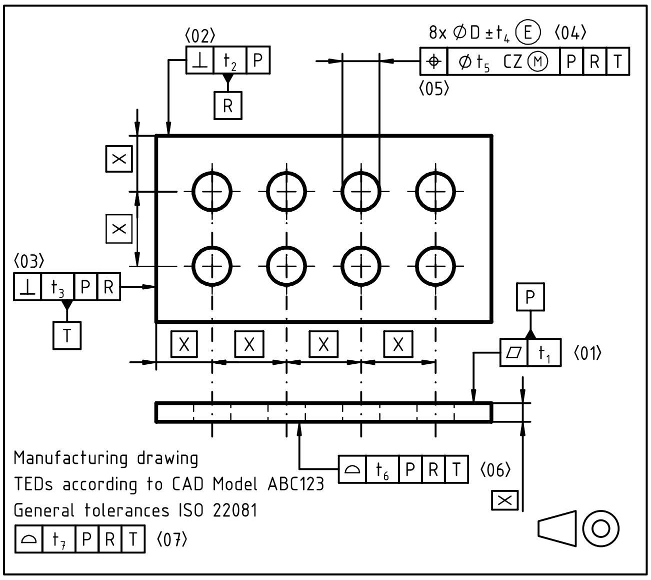

Figure 3: Geometric manufacturing specification for the case study.

(datum R); for the pose description only one point is considered (movable datum target K1).

The reference system is explicitly indicated and flag note 1 describes the type of quantity that is requested when assessing the hole locations. The deviations of interest are the deviation of the intersection point between the axis of the maximum inscribed cylinder and the nominal median plane from the nominal axis. Therefore an association criterion is needed to avoid ambiguity in the determination of the deviation: the associated maximum inscribed feature is invoked. Further, the reporting of x and y deviations in the coordinate system indicated allows effective feedback to the manufacturing process.

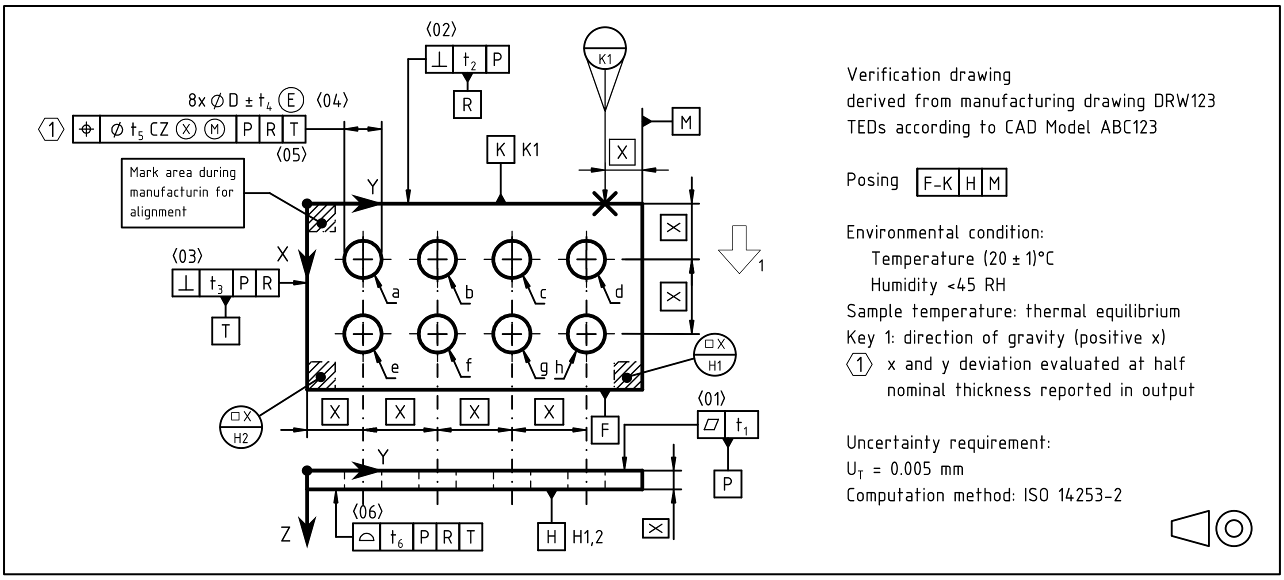

Figure 4: Geometric verification specification dedicated to process tuning.

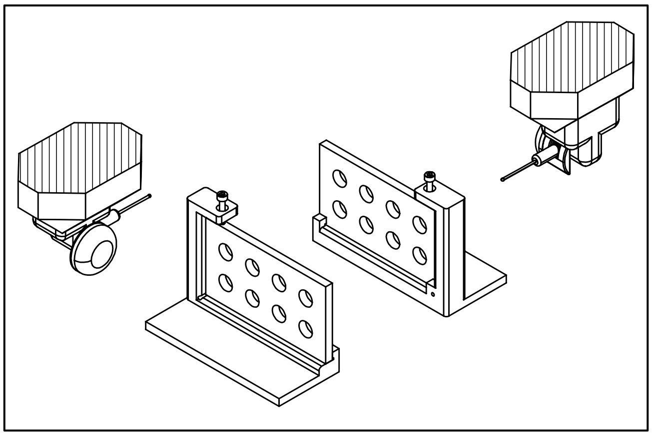

Figure 5: Example of posing described by the verification geometric specification in Figure 4.

5. Conclusions

This paper refines a definition of the *geometric verification specification*; its different aims for metrological inspection are presented and discussed, showing that different requirements in terms of measurement time and results needed will influence the specification. Requirements to control uncertainty contributors in the metrological process are also included in this specification. This work falls within the context of "Design for Metrology" where the design needs meet the constraints of a measurement process [18]: the functional design is still respected, but verification-specific information is captured in the verification specification.

A remaining question is "should the designer be responsible for this information, or the metrologist?" It is unreasonable to ask designers to become experts in the field of metrology and the knowledge required to wisely choose the right measurand/process while assuring the appropriate uncertainty is beyond the capability of a common metrology operator. The responsibility should be given either to specialized personnel capable of linking metrology and design, or to appropriate teams with the combined knowledge needed.

The example given shows a possible interpretation for a simple part. The current ISO GPS system provides adequate symbology for the geometric requirements of verification specifications. Nonetheless, it is also evident that for specific applications such as the requirement to report directional deviations of features, there is room for improvement, e.g. defining appropriate symbology.

The development of geometric verification specifications provides challenges both for research and standardization and is worthy of deeper investigations to fully define its application within the ISO GPS system, beyond the current ISO/TS 21619. The use of a geometric verification specification to support SPC and capability index computation can be explored, and test cases of these specifications could be subjected to industrial review to verify the benefits in industrial contexts. As yet, this work still does not address the actual conversion of a higher-level specification into a geometric verification specification, nor does it address industrial constraints to its application. Both points are suitable for future research.

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