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Modular cost model for Tolerance allocation, Process selection and Inspection planning

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Abstract

The need for highly reliable and precise products has forced industries to study potential uncertainties during designing needed parts. The reliability and acceptance of the product rely on several factors and tolerancing activity plays an important role to assure that the manufactured product meets the requirements. The importance of tolerancing activity can be noticed once designers prefer tight tolerances to ensure product performance and in contrast manufacturers want loose tolerances to reduce manufacturing and assembly complexity and then cost, to decrease the non-conformance rate. Therefore, tolerance allocation and inspection-planning design can be formalized as an optimization problem which the objective function represents the cost impacted by several aspects of the quality management: cost of failure, cost of the inspection. This paper details a modular cost model which includes four components: the manufacturing cost, the inspection cost, the scrap cost (internal failure), and the cost of external failure. Moreover, to improve the efficiency of the cost model, it integrates several factors such as frequencies of the monitoring and inspection activities, probability of conformed product, probability of non-detection of non-conformity, and probability of non-detection of confirmed. The applications of this model are illustrated and demonstrated through an industrial case study.

Keywords: Performance indicators, Tolerance allocation, Inspection planning, Systems optimization.

1. Introduction

Nowadays, the need for highly reliable and precise products is challenging industries. Consequently, this need has forced companies and more specific designers to study potential uncertainties during designing needed parts. The cost has been defined as one of the most used Key Performance Indicator (KPI) of product development. In the field of manufacturing and production, the cost is usually the first objective function of an optimization problem. Economically, companies attempt to involve and implement various quality improvement programs to have a competitive position [1]. The cost-efficiency of the quality management depends on several factors resulting in a quality problem such as the inefficient design of products (tolerance allocation) [2], not capable production techniques (manufacturing resources selection), defective equipment, and metrology errors [3, 4].

Production metrology is the fundamental tool to gain information and knowledge in all phases of the life cycle of any product to help link the separate processes [4]. However, it must be productive in an economic way, both cost-efficient and relevant to satisfy the single process requirements of information [5]. This matter was the subject of a CIRP Keynote Paper in 1977 [6], in which J. Peters raised the questions for

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industrial metrology: Why measure? What to measure? Does measurement pay? In addition, Kunzmann et al. [5] analyzed the role of metrology in production and demonstrated how metrology can generate economical value in manufacturing. They illustrated different ways to evaluate the benefits of metrology and to maximize the benefit of metrology investment through the supply chain. All these issues underlined how production metrology is important and why developing effective production metrology (PM) integrated with a comprehensive quality management system (QMS) has become one of the most vital tasks for today's executives [3].

The cost factor is not the only indicator to be considered during the production and the metrology phases. Designers want tight tolerances to ensure product performance; manufacturers prefer to loosen tolerances to reduce manufacturing and assembly costs. Tolerance plays an essential part in design and manufacturing. Since the role of tolerances in a life cycle varies from stage to stage, depending on their design objectives, it is a crucial task for designers to determine a tolerance meeting the design objectives and production resources. To analyze compromise solutions, the primary aim is to define the objective function. The cost modeling for the assessment of the relevance of a variation management strategy is a key issue. In fact, the cost assessment becomes a key activity to improve the tolerance allocation, to select the fittest manufacturing resources, and to generate the best inspection allocation planning [7, 8].

Nomenclature

C_{Manu}	Cost of manufacturing activities of a product
C_{Monit}	Costs of monitoring activities
C_{Inspct}	Costs of inspection activities
$OccP_{Monit}$	Occurrences (or frequencies) of the monitoring activities
$OccP_{Inspct}$	Occurrences (or frequencies) of the inspection activities
$C_{prdscrpng}$	Cost of product scraping and recycling
$C_{prdmaintnc}$	Cost of warranty, product liability claims and recall
P_c	Probability of conformed product, which depends on manufacturing imperfections and component tolerances
α	Probability of non-detection of non-conformity (measurement uncertainty)
β	Probability of non-detection of conformity (false alarm) (measurement uncertainty)
$P_c.(1-\alpha)$	Percentage of marketable conformed products
$(1-P_c).\beta$	Percentage of marketable non-conformed products
$(1-P_c).(1-\beta)$	Percentage of detected non-conformed products
$P_c.\alpha$	Percentage of undetected non-conformed products

Therefore, we propose a modular cost model, which supports the assessment of the impacts of decisions performed at each step of the quality management process: tolerance allocation, inspection planning, and so on. To do so, the needs of each step are formalized (in Section 2). The applications of this model are illustrated through an industrial case study where tolerance allocation and inspection planning optimization are addressed in section 4.

2. Related works in tolerance allocation and inspection planning

The allocation of design and manufacturing tolerances has a significant effect on both manufacturing cost and quality. Designers want tight tolerances to assure product performance; manufacturers prefer loose tolerances to reduce production cost. Indeed, tolerances are allocated to ensure the respect for geometrical product requirements and to achieve optimal manufacturing cost. Three tolerance synthesis techniques are used: rules-based synthesis, knowledge-based synthesis, and optimization synthesis [2]. The optimization approach is commonly based on a parametric model of the tolerance cost [8-10].

Additionally, the context of tolerancing can be explored where it is more focused on complex systems such as mechanical assembly products. Sivakumar et al. [11] developed a concurrent tolerancing model which optimizes over-constrained process tolerance involving dimensional and geometrical tolerances (DGTs). Rezaei Aderiani et al. [12] developed a selective assembly technique using a variation simulation tool for sheet metal assemblies. The authors studied the impacts of batch size manufacturing and adapted a tolerance optimization algorithm to obtain the best-suited mating combinations. Hallmann et al. [13] investigated the impact of an over-constrained assembly system with gaps in tolerance optimization. A cost-tolerance optimization model was established to ensure model accuracy in time-consuming applications while providing cost-optimum tolerance values. In a more current study, Tsutsumi et al. [14] integrated product design, process planning and production planning optimization in multi-product assembly assessing the investment efficiency and reduce the overall production cost.

Armillotta [15] provided a comprehensive review of the parametric cost-tolerance functions and investigated the models' inconsistencies due to parameters variabilities. The author proposed a consistent estimation of the parameters for the reciprocal power function.

An inspection activity by measuring specific characteristics allows for making decisions on conformity assessment, process monitoring, and statistical process control. Pfeifer [16] and Zhao et al. [17] defined inspection process planning as a production process planning step that determines which product characteristics should be inspected, where, and when. Rezaei-Malek et al. [7] investigated and classified the literature based on the optimization formulation. They stated: "Minimization of the total expected cost is the most common form of the objective function in the literature. Total cost generally includes different cost components as production, inspection and failure costs."

Mohammadi et al. [1] developed a new optimization framework for process inspection planning with multiple quality characteristics. They developed a mixed-integer mathematical programming model to minimize the sum of manufacturing and warranty costs. Colledani and Tolio [18] presented a general theory to combine quality, maintenance, and production control contexts to analyze the production rate of conforming parts in manufacturing systems with progressively deteriorating machines and preventive maintenance. They improved the accuracy of the cost model by taking into account the dependency between the product quality and the machine state.

The conclusion and gaps in the overview of the tolerance allocation and inspection planning problems can be concluded in the following questions:

1. How can integrate different types of tolerances into the cost-tolerance optimization model?
2. How can designers ease off cost dependencies and have an adaptable cost model?
3. How accurate is the proposed cost model and would it fit in real scenarios?

3. Cost model

Cost modeling aims at estimating product cost while it has undergone several activities such as processing, inspection, scrap, etc. Most product cost models follow a single process plan and determine the corresponding cost which does not take into account the multiplicity of the process plans. In this regard, Shah et al. [19] studied more in-depth and developed a process-oriented risk assessment methodology to develop a global risk indicator. Furthermore, the authors proposed the risk identification process using an objective-driven approach and integrated it with other assessment techniques such as process model and simulation. Therefore, in this section, we propose a cost model based on Activity Based Costing (ABC): Quality-driven which intends to balancing the manufacturing cost and product conformance throughout the tolerance and variations analysis [8]. It is the total cost of a marketable product which includes four costs:

- the manufacturing cost,
- the inspection cost,
- the scrap cost (internal failure),
- the cost of external failure.

These four costs are weighted by the occurrence or/and the efficiency of related activities. The strategy is then to develop a global modular accurate indicator. Global: this indicator represents the cost of the product; it cannot be split to extract the cost of one tolerance. Modular: it is possible to subdivide the model into smaller modules (thanks to activity-driven modularity) that can be independently defined and then used in different ways. Accurate: each component and factor could be accurately assessed.

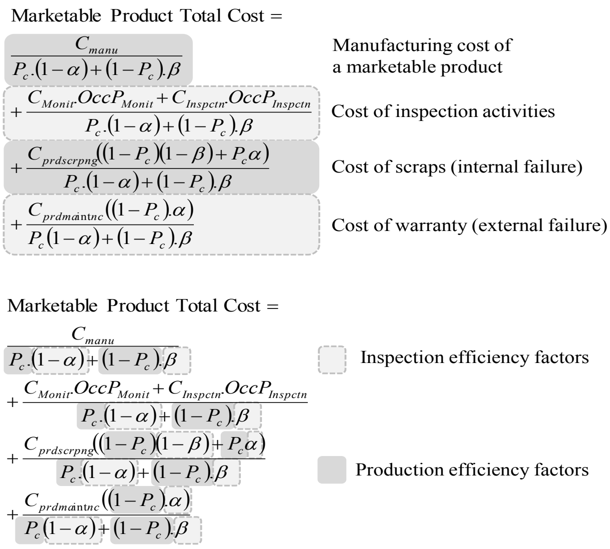

Fig. 1. Components and factors of the cost model

Figure 1 demonstrates all components and all factors of the proposed cost model. As mentioned in the conclusion of section 2, several components and various factors need to be integrated to improve the robustness of the decision-making based on this KPI. This model could be used for tolerance allocation, inspection-planning optimization, and for process planning (the process capabilities of the selected process plan influence the production efficiency). For more clarification of the modular cost model proposed in Fig. 1, the rest of this section studies the impact of tolerance allocation and inspection planning on an illustrative example.

3.1. An illustration of the tolerance allocation cost

During the manufacturing process, to meet the requirement of the product and to yield the component's dimensions, it is necessary to define manufacturing tolerances to conformed product's functional requirements. In literature, varied manufacturing cost models have been developed to illustrate the relation between tolerancing and manufacturing cost. For instance, several types of manufacturing parametric cost models were defined respectively: Exponential function (Ep), reciprocal power function (RP), and Cubic Polynomial (Cubic-P) [20]. However, in this paper, a flexible cost-tolerance model is developed which statistically will be impacted by the conformity rate of the component to be processed. The model is no more dependent on cost model coefficients and will be directly associated with a constant manufacturing cost value.

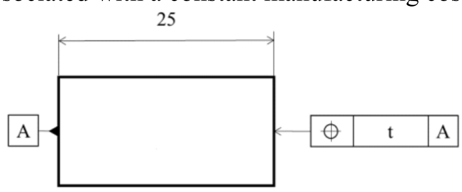

Fig. 2. An illustrative assembly design

For the sake of simplicity, let us assume part A illustrated in Fig. 2. In this figure, a dimensional deviation (Dev) is considered which is modelized by a random variable $Dev \sim N(0, \sigma)$ and σ is the standard deviation representing manufacturing imprecision. Therefore, the conformity rate of parts (P_c) defines as follows:

$$P_c = P(Nom + Dev \in [LSL, USL]) \quad (1)$$

Based on Eq. (1), the behavior of the proposed manufacturing system depicts in Fig. 3 which demonstrates the tolerance allocation cost developed following the same behavior as the one given in the literature (please read [21]). The same curve is resulted following improving the tolerance allocation cost model and relieving the model from coefficient dependencies and integrating tolerance in the definition of part conformities.

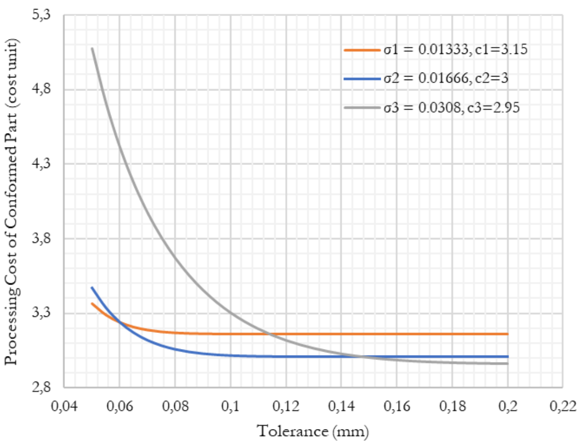

Fig. 3. The tolerance allocation cost behavior with change in allocated tolerance

In this context, processing cost is a constant value that easily can be modified and is independent of various coefficient parameters.

3.2. An illustration of the inspection planning model

Once the tolerance is allocated, inspection is applied to check whether the process is valid or not. Inspection planning deals with the tolerances obtained as inputs and following that would inspect if the process performed satisfies the tolerances or modification is required. Thus, design tolerances impact on the decision, producers also may face uncertainties for the measurement tools utilized. To be clearer, as in previous section, let us assume part's dimensional variation follows a normal distribution $Dev \sim N(0,\sigma)$ where σ refers to standard deviation representing manufacturing imprecision. Moreover, due to inspection uncertainties, we assume that measurement tool uncertainty follows a normal distribution where $U_i \sim N(0,\sigma_{Ui})$ and σ_U illustrates measurement tool deviation. Following these bases, the uncertainties of the inspection will impact on the product conformity rate which need to be estimated. To study the impact of inspection uncertainties, two common failures need to be examined, respectively Type I and Type II failure rates. Type I failure rate (α) happens once the process is confirmed however the inspection reject it and Type II failure rate (β) occurs when a non-confirmed process returns as a confirmed process from the inspection. Following equations defines these probabilities:

$$\alpha = P(|Nom + Dev + U| \geq USL|\ |Nom + Dev| \leq USL) \quad (2)$$

$$\beta = P(|Nom + Dev + U| \leq USL|\ |Nom + Dev| \geq USL) \quad (3)$$

For instance, as outputs of previous section, a process deviation equals to $\sigma_1 = 0.0308\ (mm)$ and tolerance equals to $t_1 = 0.1\ (mm)$ are obtained. Furthermore, to inspect the part's dimension whether the process is confirmed or not, two types of measurement tools are used, low cost (U1) and high cost (U2), respectively. The measurement tools' specifications are given in Table 1.

Table 1. Measurement tools' specifications

	σ_{Ui}	Cost
U1	0.00266	1
U2	0.00133	1.2

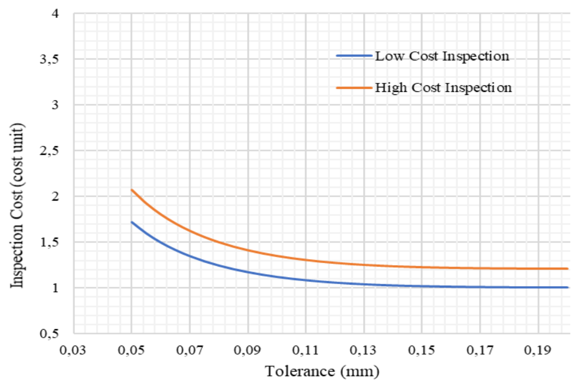

Fig. 4. Inspection cost behavior regarding different types of tools and tolerances

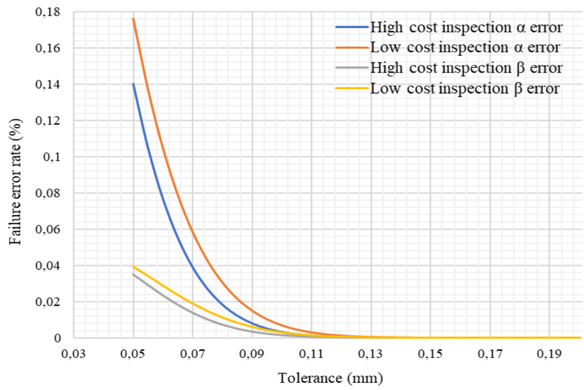

Fig. 5. Failure errors rate comparison of high and low-cost inspection tools

As illustrated in Fig. 4, the decision of inspecting the process or not and which measurement tool to be selected has a direct impact on the inspection and in general the manufacturing cost. Moreover, Fig. 5 compares failure errors rates of high-cost and low-cost inspection tools. In this section, a mathematical model was proposed, and the tolerance allocation model and inspection planning model were illustrated by simple cases. Furthermore, in the next section, the applicability of the model is illustrated using a real case.

4. Application

The industrial case study is an automotive gear pump (Fig. 6). An automotive gear pump is considered a high precision product that must be low-cost too. The required function delivers oil with the required pressure and speed, therefore the considered functional requirement is the efficiency of the pump which is impacted by several backlashes. These backlashes are between the gears and the casing as well as between the gears and shafts. Too small backlashes result in friction and too much of them result in internal flow loss, consequently efficiency reduction. Furthermore, to study the behavior of the system and the impacts of backlashes, two applications are proposed: tolerance synthesis (so-called allocation), and inspection planning optimization.

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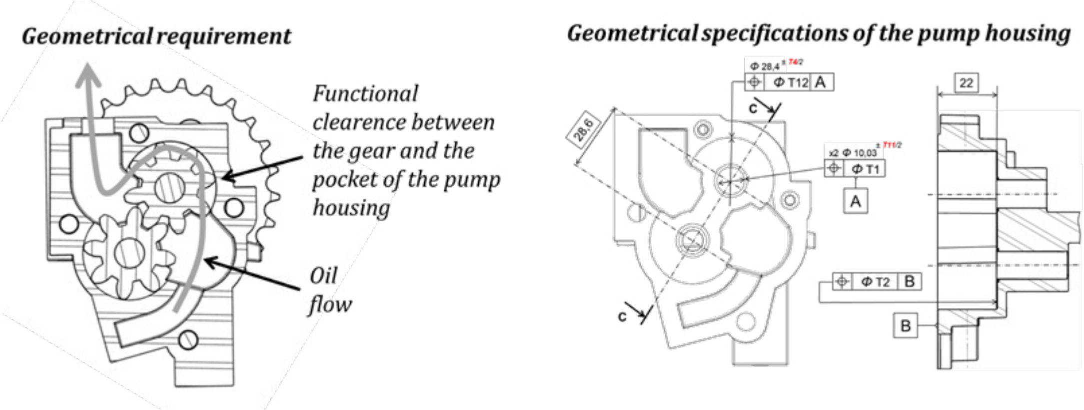

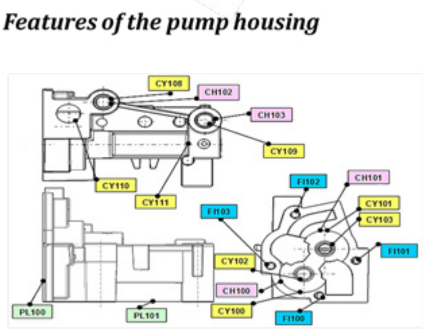

Process plan and process capabilities

	Process operation	Parameter value			
		MT (min)	Cp	Pp	AP
1	Rough milling PL100	.148	2	1.50	1→13
2	Rough milling PL100	.166	2	1.50	2→14
3	Rough milling PL101	.133	2	1.66	3→15
4	Boring CY110	.154	1.60	1.33	4→10
5	Rough drilling CY108 & CY109	.09	2	1.66	5→10
6	Chamfering CY108 & CY109	.25	2	1.66	6→6
7	Chamfering CY100 & CY101	.257	1.50	1.20	7→15
8	Boring CY100	.257	1.50	1.20	8→15
9	Boring CY101	.122	1.66	1.30	9→12
10	Rough drilling CY102 & CY103	.109	1.66	1.40	10→12
11	Rough drilling CY111	.134	1.66	1.40	11→15
12	Boring CY108 & CY109	.122	1.30	1.10	12→15
13	Boring CY102 & CY103	.122	1.30	1	13→15
14	Boring CY111	.117	1.66	1.33	14→15
15	Finish milling PL100	.129	1.66	1.33	15→15

Fig. 6. Gear pump requirement, casing tolerances and casing process plan

For the automotive gear pump, 13 tolerances are identified (only some of them of the casing are shown in Fig. 6) and are required to be allocated. Additionally, Fig. 6 details the production time, the operation capability, the failure rate, and the allowable places to perform the inspection for each quality characteristic. Therefore, the tolerance allocation is proposed to evaluate the marketable product total cost regarding the allocated tolerances. A genetic algorithm is adapted to evaluate and find the optimal solutions to this problem.

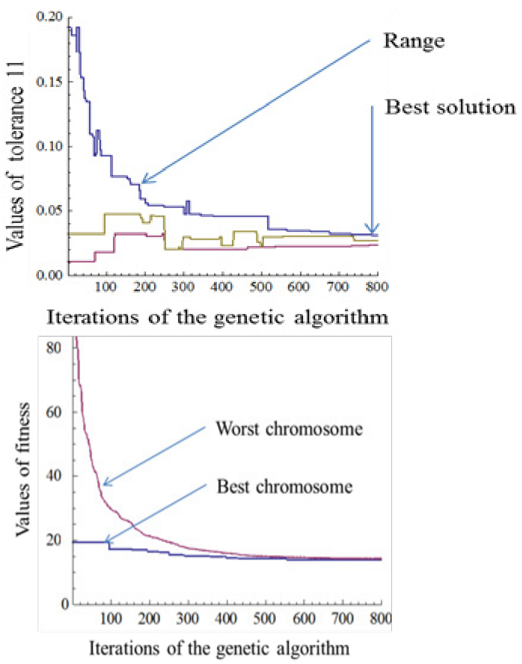

Fig 7. The tolerance allocation optimization results [20]

Figure 7 depicts the evolution of the marketable product total cost and the convergence of the tolerances to the best values. Afterward, the inspection planning related to the main part of the gear pump with 15 quality characteristics is studied [21].

The Pareto frontier of the inspection planning problem is illustrated in Fig. 8, in which the dash and solid lines represent the Pareto frontiers of the problem with deterministic and uncertain parameters, respectively. One of the optimal solutions is: quality characteristics number 2, 4, and 6 to 12 need Monitoring Inspections (MI) and quality characteristics number 7 and 11 to 15 need Conformity Inspections (CI).

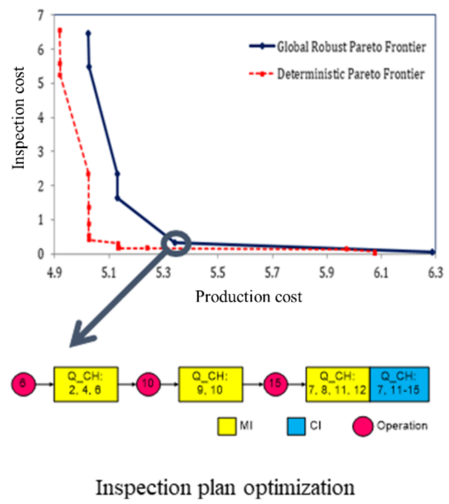

Fig. 8. The inspection planning optimization results [1]

Some of them are performed after the operation 6, and after the operation 10, and all conformity, inspections are performed after the last manufacturing operation.

5. Conclusion and Future Work

Product conformance and its corresponding manufacturing cost are dependent on vast types of uncertainties and activities such as manufacturing, inspection, etc. Tolerancing and inspection have significant effects on both manufacturing cost and conformance, consequently, the right decisions of the optimal value of allocated tolerances and a suit inspection plan can deeply impact on the quality and cost of the product. Therefore, to help designers, the main contribution of this paper is the proposition of a global modular accurate cost model which considers the efficiency of activities of the product lifecycle. The proposed model is based on Activity-Based Costing which is a promising approach regarding classical parametric models thanks to its sensitivity, scalability (modular model) and accuracy.

The model was implemented into illustrative cases steps which the first step allocates tolerances using an improved and flexible cost model no more dependent on cost model coefficients and integrates tolerance in the definition of part conformity rate. Afterward, the second case can be applied once the tolerance is allocated to inspect whether the process is valid or not. All components of the global cost model are based on well-known (and easy to identify and assign) data of the production process (as for instance: quality rate, inspection errors); therefore, its deployment is a simple step. Due to its flexibility this cost model and be integrated into an optimization approach as part of an objective function. For the future outlook of the current paper, it can be interesting to propose an adaptive tolerancing which can respond to complex engineering designs with variety of tolerances such as gear's structure, and to propose an adaptive production strategy taking to account production uncertainties, assessing both technical and economic assessments of the designed product.

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