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เพื่อให้การนำเสนอผลงานวิจัยเป็นไปด้วยความเรียบร้อย จึงใคร่ขออนุมัติทุนสนับสนุนเพื่อนำเสนอผลงานวิจัยดังกล่าว เป็นจำนวนเงิน 40,000.- บาท (สี่หมื่นบาทถ้วน) โดยมีค่าใช้จ่ายในการนำเสนอผลงานทั้งสิ้น 51,200.- บาท (ห้าหมื่นหนึ่งพันสองร้อยบาทถ้วน) ดังนี้

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Multi-Criteria Selection Problem of Part Orientation in 3D Fused Deposition Modeling based on Analytic Hierarchy Process Model: A Case Study

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Abstract - **Additive manufacturing (AM) or 3D printing (3DP) is now perceived as an industrial revolution technology in this digital 4.0 era. It has become popular in various industrial fields thanks to its key advantages in almost unlimited design freedom and material efficiency. However, challenges in AM process planning still exist and require substantial studies. In this research, we study an operational-level, decision-making problem for the orientation selection of the 3DP part to understand process instability and efficiency issues. In addition, as quantitative methods to determine the part orientation accounting for user's knowledge and preferences are limited, we illustrate economical and mechanical-desire preferences from a decision maker using analytic hierarchy process (AHP) framework. Trade-offs among conflicting criteria for parts produced from fused deposition modeling (FDM) are analyzed and compared to obtain the optimal part orientation to be produced. The robust result shows that a perpendicular direction affects how part is to be selected**

Keywords - **Multi-criteria decision making; Analytic hierarchy process (AHP); Part orientation; Additive manufacturing; 3-dimensional printing**

I. INTRODUCTION AND MOTIVATION

Additive manufacturing (AM) has become popular in various industries, not only for high-quality industrial use of three-dimensional printing (3DP), but also for personal 3DP use. These three-dimensional (3D) printers and technologies are categorized by materials and operations, each of which has their own advantages and disadvantages [1-3]. Whereas advantages of the AM include reduction of tooling, agile manufacturing, reduction in inventory, and part consolidation; challenges are noted for cost of machines and materials, quality assurance, and supply chain perspective. The top three AM technologies are stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM) [4]. In contrast to the traditional method, AM can provide almost a perfect design freedom for part fabrication with material efficiency. Although manufacturing companies recognize the significance of AM technologies, the applicability of 3DP technology is challenged by low cost-efficiency, quality variation, and process planning [5-8]. Among many process planning problems, the part orientation is one critical factor that affects processing time, part cost, surface quality, and anisotropic properties of a 3DP part [9].

Orientation of a part refers to the building direction with respect to the part being fabricated by the AM machine. Two key tasks to solve the part orientation concern are to determine the alternative orientation and to select the most suitable orientation among these alternatives [10]. As a selection of the part orientation can affect multiple and conflicting factors, it can be viewed as the multi-criteria decision-making (MCDM) problem. Although MCDM have been increasingly used by decision makers (DMs), an application of MCDM in AM is limited. MCDM has been used in a variety of applications to support decision-makers facing decision and planning problems that a unique optimal solution does not exist and decision-maker's preferences are involved [11-13]. Among MCDM methods, analytic hierarchy process (AHP) framework is a structured technique that can support complex decisions through direct comparison among alternatives, which helps DMs to find one decision that best suits their goal and their understanding of the problem [14].

Researchers have recently studied the impacts of the part orientation in AM and proposed models to aid a process planning for the part building [15-16]. However, existing models that account for process planner's preference and knowledge are lacking. In addition, studies that compare 3DP parts fabricated from different AM technologies are limited. In this research, we examine the part orientation decision making using AHP methodology. Initially, the orientation alternatives are generated based on the concept of convex envelope of a part visualized as the smallest convex set that contains a part. Next, six conflicting criteria are determined (i.e., build time, build cost, surface quality, part accuracy, mechanical properties, and support volume). Then, these orientation alternatives are fabricated from a FDM machine and criteria data are collected and compared for qualitative and quantitative measures. Two types of DMs (i.e., economical and mechanical-desire) are next illustrated in the study. The validity of the algorithm is then verified with technical staffs to improve optimal, effective process planning in the AM.

The remaining sections of this study are organized as follows. We discuss multi-criteria selection problem of part orientation in AM based on AHP model in Section II. Next, an experimental case study and results are discussed in Sections III and IV, respectively. Finally, Section V presents our research conclusions and outlines directions for future research.

II. ANALYTIC HIERARCHY PROCESS METHODOLOGY

We illustrate the MCDM-based part orientation framework incorporating AHP technique in this section. AHP has been applied in different fields including planning, selecting the best alternative, allocating resources, resolving conflict, optimization, and so on [14, 17]. It is essentially based on three main operations; hierarchy construction, priority analysis, and consistency verification. AHP works by transforming the comparisons, which are most of the times empirical, into numeric values that can be further processed and compared. The weight of each factor allows the assessment of each one of the elements inside the hierarchy, which is the main distinctive contribution of the AHP when contrasted to other techniques.

Initially, the hierarchy structure can be constructed for the top (i.e., goal or objective), the intermediate (i.e., criteria and sub-criteria), and the bottom (i.e., alternatives) levels. All of the pairwise comparison matrices, with each size of $n \times n$, are then constructed and normalized where n is the number of evaluated criteria. The comparison between two elements can be done in different ways, where the relative importance scale from 1 (i.e., equal preference) to 9 (i.e., extreme preference) is widely used [14]. These comparisons can be recorded in a positive reciprocal matrix, *A*, as shown in (1). In making judgements, the DM can incorporate experience, knowledge, and hard data. Notice that the diagonal elements are always 1 and we only need to fill the upper triangular matrix, such that if the judgement value is on the left side of 1, we put the actual judgement value; otherwise, we put the reciprocal value if the judgement value is on the right side of 1. Thus, there are $[n \times (n-1)]/2$ judgements required to develop the matrix. Next, the normalized principal Eigenvector (p) is calculated and the principal Eigenvalue or maximum Eigenvalue ($\lambda_{\max}$) is obtained. The Eigenvector shows the relative weights between each criterion obtained by computing the arithmetic average of all criteria, where the sum of all values in the vector is one. The $\lambda_{\max}$ can be calculated from the summation of products between each element of Eigenvector and the sum of columns of the reciprocal matrix (2).

Then, it is important to capture enough information to decide whether a DM has been consistent in the choices that are provided. Thus, the consistency check is next performed by calculating the consistency index (*CI*), selecting the random consistency index (*RI*), and evaluating the consistency ratio (*CR*) for each matrix. In particular, the *CI* can be calculated using (3). Next, in order to verify whether the *CI* is adequate, the *CR* can be calculated based on the ratio between *CI* and *RI*, such that the *CR* value will be considered having an acceptable consistency if the resulting ratio of *CR* is less than 10% (4). The *RI* based on the average CI of 500 randomly filled matrices is as follows - (*n, RI*) pairs: *(1, 0.00), (2, 0.00), (3, 0.58), (4, 0.90), (5, 1.12), (6, 1.24), (7, 1.32), (8, 1.41), (9, 1.45),* and *(10, 1.49)*. Finally, an overall, global ranking of decision alternatives can be analyzed, which adopts an additive aggregation with normalization of the sum of the local priorities to unity (5).

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \dots & a_{ji} = 1/a_{ij} & 1 & \dots \\ a_{n1} & \dots & \dots & 1 \end{bmatrix} \quad (1)$$

$$A \cdot p = \lambda_{\max} \cdot p \quad (2)$$

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (3)$$

$$CR = \frac{CI}{RI} \quad (4)$$

$$g_i = \sum_j w_j l_{ij} \quad (5)$$

,where A is the comparison matrix; a_{ij} is the comparison between i and j based on the importance scale; p is the normalized principal Eigenvector; $\lambda_{\max}$ is the maximal Eigenvalue; g_i is the global priority of the alternative i; l_{ij} is a local priority; and w_j is the weight of the criterion j.

III. EXPERIMENTAL CASE STUDY

A. Orientation Alternatives

In practice, only a certain number of orientation alternatives are practical in the process planning. The test model in Fig. 1 with the size of 70×25×30 mm^3 similar to [16] is used to demonstrate the determination of orientation alternatives to aid a comparative study. Fig. 1a) and 1b) show orientation alternatives based on the concept of convex envelope and build direction of the model, respectively. Mathematically, the convex envelope or convex hull of a set of points is the smallest convex set that contains all the points. Thus, six orientation alternatives can be identified from this illustrative part. We note that orientation alternatives 2 and 4 are differentiated, such that alternative 2 is oriented with sharp angle between the printing platform and part, whereas alternative 4 is perpendicularly oriented between the printing platform and part. Fig. 2 illustrates the AHP-based multi-criteria selection problem of part orientation in AM used in this analysis.

B. Multiple Criteria for AM Orientation

In this study, we illustrate six key criteria discussed in the literature as important factors affected by an orientation alternative.

1) *Build time (BT) criterion*: Build time is related to the time spent on layer scanning, which is dependent on

the number of slices. The number of slices is also determined by layer thickness and the height of the part from the z building direction. Thus, it follows that different orientations impact greatly the build time.

2) *Build cost (BC) criterion*: Build cost refers to the resources consumed during the manufacturing of a part in AM, which usually contains direct (e.g., material) and indirect cost (e.g., machine, energy, labor, time, etc.). It follows that an orientation of a part will have an important effect on the part cost.

3) *Surface quality (SQ) criterion*: Parts which are typically parallel or perpendicular to the build orientation will tend to have a better surface roughness or surface finish than those whose face normal has an angle to the build direction. Thus, the build direction of the part will affect the surface quality of a part and the surface quality should be considered as a key attribute.

4) *Part accuracy (PA) criterion*: Parts accuracy refers to the difference between the produced part and the design model. Part orientation can affect both shrinkage and distortion, which are the main factors in AM resulting in this difference. Thus, part accuracy is one important attribute affected by the orientation.

5) *Mechanical properties (MP) criterion*: Properties of a part produced by AM are found to be anisotropic (i.e., the property of being directionally dependent). Other properties, such as density, thermal, and electric conductivity are also affected by the build orientation.

6) *Support volume (SV) criterion*: Support structure is needed in some particular AM processes, such as FDM for over-hangings. As the building orientation affects the quantity of over-hangings of a part, it follows that the building direction also impacts support volume.

C. Decision-Maker Preferences

We illustrate an experimental design for two types of DMs including economical and mechanical-desire DM. The economical DM illustrates a user who desires to pay less for a printed part regardless of other factors (e.g., pay more attention to build cost (*BC*) and build time (*BT*)). On the other hand, the mechanical-desire DM is willing to pay more and scarify other factors as long as the printed part has a high performance and good mechanical properties (e.g., prefer mechanical properties (*MP*)).

D. Part Fabrication

We fabricate parts for all orientation alternatives from FDM printer using PLA material and Sprout printer from Former's Farm at the center for 3D advanced additive manufacturing at Ulsan National Institute of Science and Technology (UNIST). Next, to evaluate each criterion for printed part orientations, a questionnaire filled out by technical experts, part testing, and Magics™ software developed by Materialise are used to obtain necessary information to aid a DM to evaluate each orientation alternative. In particular, data related to the build time, build cost, and support volume are quantitative and are estimated from Magics™; whereas surface quality, part accuracy, and mechanical properties are combined qualitative and quantitative data obtained from part test and expert opinions. Figs. 3(a) and 3(b) illustrate printed parts from FDM and part accuracy test between CAD file and printed part. The summary of the data is illustrated in Table 1. It is clear that data for all criteria from altered orientation alternatives are conflicting with each other. For example, whereas build cost for alternatives 1 and 4 are the lowest, part accuracy of alternative 5 is superior.

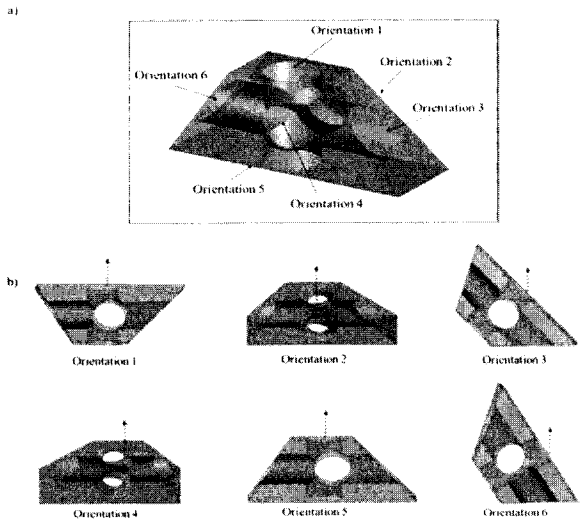

Fig. 1. Orientation alternatives a) based on the convex envelope; b) based on the build direction.

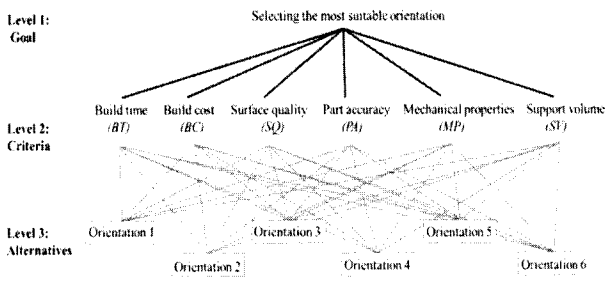

Fig. 2. Hierarchy structure of the AHP-based part orientation model

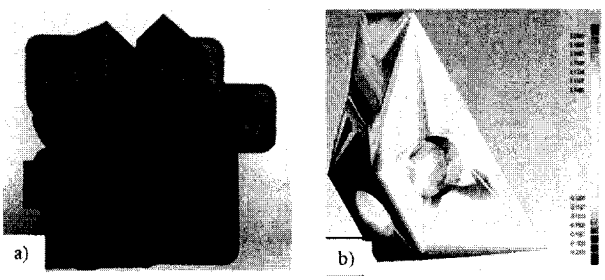

Fig. 3. a) part fabrication for all orientation alternatives from FDM; b) part accuracy test between CAD model and the printed part

TABLE I
TEST DATA FROM FDM TO AID AHP-BASED DECISION MAKING

	Ori. 1	Ori. 2	Ori. 3	Ori. 4	Ori. 5	Ori. 6
BT (*h*)	4.5-5.0	5.0-5.5	4.5-5.0	4.0-4.5	4.5-5.0	4.5-5.0
BC ($)	$12	$15	$13	$12	$13	$13
SQ (R_a)	R_a 5.58	R_a 5.45	R_a 13.06	R_a 2.75	R_a 9.98	R_a 11.22
PA (*mms*)	0.128 mms	0.127 mms	0.146 mms	0.109 mms	0.103 mms	0.141 mms
MP (*5-1*)	Score 2	Score 3	Score 1	Score 5	Score 4	Score 1
SV (*g*)	3 grams	1 gram	5 grams	1 gram	3 grams	4 grams

IV. RESULTS AND DISCUSSION

Given that there are two types of DMs in this experiment (i.e., economical and mechanical-desire), two comparison matrices, each with the size of 6×6 based on six criteria, are needed with respect to the criteria level. Then, six comparison matrices, each with the size of 6×6 based on six alternatives, are required for each criterion at the alternatives level. The pair-wise comparison matrix the criteria filled by the economical DM is illustrated in Table 2. For example, the economical DM compares among all the criteria such that the *BC* is moderately preferred to *BT* criterion and is either strongly or strongly to very strongly preferred to *SQ, PA, MP,* and *SV* criteria. Next, the matrix is normalized, the Eigenvector is calculated, the maximum Eigenvalue is obtained, and the CI and CR are calculated as shown in Table 3. The comparison for the criteria matrix is used to set priorities in terms of importance in contributing to the overall goal.

The matrix is first normalized by dividing each element of the matrix by its column total. For example, the value 0.19 in Table 3 is obtained by dividing 1 by 5.42, the sum of the column (1+3+1/3+1/3+1/4+1/2). Next, the priority vector or the Eigenvector in Table 3 is approximately obtained by computing the row average. For example, the priority of *BT* (i.e., 0.21) is calculated by dividing the sum of all values in the row (0.19+0.16+0.29+0.23+0.20+0.16) by the number of criteria (i.e., 6). Then, λ_{max} can be calculated from the summation of products between each element of Eigenvector in Table 3 and the sum of columns of the matrix in Table 2. That is, 6.44 can be obtained from (0.21×5.42) + (0.45×2.07) + (0.12×10.33) + (0.10×12.83) + (0.04×20.00) + (0.09×12.33). Next, the CI can be calculated, such that CI = (6.44-6)/(6-1) = 0.09. After the RI is properly chosen (i.e., RI = 1.24), the CR can be calculated as CR = 0.09/1.24 = 0.07. Since the value of CR is found to be less than 10% (i.e., 0.1), the judgements are found to be acceptably consistent. In addition to the pair-wise comparison for the criteria, the same pair-wise compassion procedure is preceded for the decision alternatives with respect to each criterion in the FDM process. Finally, after obtaining the Eigenvectors of the criteria for all DM types and all the Eigenvectors from each alternative relative to each criterion, we can now develop an overall priority ranking as shown in Table 4. For example, the overall, global priority (weight) of the orientation 1 with respect to all criteria for the economical DM when the FDM technology is used is 0.21, which can be computed from (0.21×0.14) + (0.45×0.3) + (0.12×0.18) + (0.10×0.09) + (0.04×0.08) + (0.09×0.11).

TABLE II
COMPARISON MATRIX FOR CRITERIA FROM ECONOMICAL DECISION MAKER

Criteria	BT	BC	SQ	PA	MP	SV
BT	1	1/3	3	3	4	2
BC	3	1	5	6	6	5
SQ	1/3	1/5	1	2	3	2
PA	1/3	1/6	1/2	1	3	2
MP	1/4	1/6	1/3	1/3	1	1/3
SV	1/2	1/5	1/2	1/2	3	1
(sum)	5.42	2.07	10.33	12.83	20.00	12.33

TABLE III
SYNTHESIZED MATRIX FOR CRITERIA FROM ECONOMICAL DECISION MAKER

Criteria	BT	BC	SQ	PA	MP	SV	Eigen vector
BT	0.19	0.16	0.29	0.23	0.20	0.16	0.21
BC	0.55	0.48	0.48	0.47	0.30	0.41	0.45
SQ	0.06	0.10	0.10	0.16	0.15	0.16	0.12
PA	0.06	0.08	0.05	0.08	0.15	0.16	0.10
MP	0.05	0.08	0.03	0.03	0.05	0.03	0.04
SV	0.09	0.10	0.05	0.04	0.15	0.08	0.09
(sum)							1.00

TABLE IV
OVERALL PRIORITY RANKINGS FOR FDM

Economical DM type

	BT 0.21	BC 0.45	SQ 0.12	PA 0.10	MP 0.04	SV 0.09	Overall Priority Vector	Rank
O1	0.14	0.30	0.18	0.09	0.08	0.11	0.21	**2**
O2	0.03	0.04	0.20	0.12	0.15	0.32	0.09	**5**
O3	0.17	0.13	0.04	0.04	0.05	0.04	0.11	**4**
O4	0.39	0.30	0.44	0.25	0.45	0.35	0.34	**1**
O5	0.16	0.12	0.08	0.43	0.24	0.12	0.16	**3**
O6	0.11	0.11	0.05	0.05	0.03	0.07	0.09	**6**

Mechanical-desired DM type

	BT 0.20	BC 0.11	SQ 0.06	PA 0.15	MP 0.44	SV 0.04	Overall Priority Vector	Rank
O1	0.14	0.30	0.18	0.09	0.08	0.11	0.13	**3**
O2	0.03	0.04	0.20	0.12	0.15	0.32	0.12	**4**
O3	0.17	0.13	0.04	0.04	0.05	0.04	0.07	**5**
O4	0.39	0.30	0.44	0.25	0.45	0.35	0.39	**1**
O5	0.16	0.12	0.08	0.43	0.24	0.12	0.23	**2**
O6	0.11	0.11	0.05	0.05	0.03	0.07	0.06	**6**

The orientation alternatives are now ranked according to their overall priorities based on all criteria and DM preferences following the AHP's goal. In particular, the economical DM ranks FDM as orientation alternatives 4, 1, 5, 3, 2, and 6 indicating that orientation 4 is the best orientation for him or her. On the other hand, the mechanical-desire DM ranks FDM from 3, 4, 5, 1, 2, and 6. It is clear that although orientation alternative 4 is ranked the best regardless of decision maker's preference, the less of ranking is affected by how more or less each criterion is favored.

V. CONCLUSION AND FUTURE RESEARH

AM processes have gained many communities' interests as they can provide several benefits in design flexibility, time-to-market reduction, high speed of the process, product customization, material savings, and so on. While an emphasis in the AM has moved towards end-use parts, some issues related to process inefficiency and instability resulting from certain factors including the orientation selection of a part still need to be addressed. This research paper presents the MCDM-based part orientation framework that incorporates AHP model allowing the consideration of multiple criteria to analyze two key tasks for the part orientation; determining the alternative orientation and selecting the most suitable one among alternatives. It is evident that there are trade-offs among these conflicting criteria when different DMs' preferences were incorporated. The robust result obtained from this study shows that a perpendicular direction clearly affects how part is to be selected. Our future works are to integrate the orientation model with the part-to-printer optimization assignment problem using the multiple-objective optimization approach and the part-location-in-the-printer problem using genetic algorithm. A more complex part could be further tested to illustrate an applicability of the proposed method and to compare the proposed framework in this paper with other techniques.

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Kasin Ransikarbum <kasinphd@gmail.com>

IEEM2017 Paper Notification (IEEM17-P-0029)

5 messages

IEEM2017 Secretariat <info@ieem.org> Thu, Jul 20, 2017 at 5:26 PM
To: kasinphd@gmail.com

Thursday, July 20, 2017

Dear Dr Kasin Ransikarbum,

Congratulations! Your paper has been accepted for presentation at the 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM2017), taking place from 10 to 13 December 2017 at Suntec Singapore. We invite you to attend the conference and will be looking forward to your presence. Details on the paper acceptance are as shown.

IEEM17-P-0029 / Multi-criteria Selection Problem of Part Orientation in 3d Fused Deposition Modeling Based on Analytic Hierarchy Process Model: a Case Study

Registration and final paper submission opens on **01 August 2017**. Please register, submit your IEEE Xplore® compliant final paper and complete your online copyright transfer by **01 September 2017**. Failure to do so may result in your presentation and paper not being included in the conference program, proceedings and any other materials produced for distribution at the conference. See also other important notes below.

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Reviewer Reports

Reviewer 1	
Grade	A - This paper is excellent and can be accepted as it is. Some minor comments are given here.
Comment	The paper is well structured, the problem is well identified and it is well situated within the literature, the methodology is adequately described and relevant to the problem. The results are coherent and useful for decision makers. I suggest to describe the results in abstract.
Reviewer 2	
Grade	B - This paper is acceptable. Minor improvements can be done in terms of organization/language/literature review etc. Some further comments are given below.
Comment	Very interesting topic and use of AHP technique. Well written paper. In section III part A, Can the authors discuss more the selection of size and shape of the fabricated part in their case study and why not other shape or size. In addition, in part B, can the authors reference the related literature of Multiple Criteria for AM Orientation. In the conclusion (section V), it is better to briefly summarize key results of the case study.
Reviewer 3	
Grade	B - This paper is acceptable. Minor improvements can be done in terms of organization/language/literature review etc. Some further comments are given below.
Comment	In this paper, the authors use the analytic hierarchy process model to solve the selection problem of part orientation in additive manufacturing. The application is new and written well. Two minor comments need to be noted. 1. The complete spelling of 3D should be unified in this paper. 2. The table title should be unified in this paper.

Kasin Ransikarbum <kasinphd@gmail.com> Fri, Jul 28, 2017 at 12:16 PM
To: Thitikan Boonkang <thitikan.b@ubu.ac.th>

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Kasin Ransikarbum and Namhun Kim

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