A procedure to estimate missing information in group decision-making with fuzzy linguistic information

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Resumen

In this paper, we present a procedure to estimate missing preference values when dealing with incomplete fuzzy linguistic preference relations assessed using a 2-tuple fuzzy linguistic approach in Group Decision-Making problems. This procedure attempts to estimate the missing linguistic information in an individual incomplete fuzzy linguistic preference relation using only the preference values provided by the respective expert. To do so, it is guided by the additive consistency property in order to maintain experts' consistency levels. Additionally, a selection process of alternatives in Group Decision-Making with incomplete fuzzy linguistic preference relations is presented. Finally, we analyze the use of our estimation procedure in the decision process.

1. Introduction

Group Decision-Making (GDM) arises from many real world situations [2]. In these problems, there are a set of alternatives to solve a problem and a group of experts trying to achieve a common solution. To do this, experts have to express their preferences by means of a set of evaluations over a set of alternatives. In this paper we assume that experts use preference relations [11, 13, 14]. According to the nature of the information expressed for every pair of alternatives there exist many different representation formats of preference relations: *fuzzy preference relations* [11], *fuzzy linguistic preference relations* [3, 4], *multiplicative preference relations* [5, 13], *intuitionistic preference relations* [19] and *interval-valued preference relations* [1].

Since each expert has his/her own experience concerning the problem being studied, there may be cases where an expert would not be able to express the preference degree between two or more of the available options. This may be due to an expert not possessing a precise or sufficient level of knowledge of the problem, or because that expert is unable to discriminate the degree to which some options are better than others. In such situations, experts are forced to provide *incomplete preference relations* [9]. Therefore, it should be of great importance to provide the experts with tools that allow them to deal with this lack of knowledge in their opinions.

In order to maintain experts' consistency levels many authors have proposed estimation procedures of preferences based on consistency criteria [9, 15, 16, 17, 18]. For fuzzy preference relations, procedures to estimate missing values were proposed in [9, 15] based on *Tanino's additive consistency property* [14]. For ordinal fuzzy linguistic preference relations, some procedures to estimate missing values were proposed in [17, 18] based on *Saaty's consistency property* [13]. However, Saaty's consistency property is defined for multiplicative preference relations and therefore it is not applicable to fuzzy linguistic preference relations. It is well known that the fuzzy translation of Saaty's consistency property coincides with Tanino's additive consistency property [8, 9]. Therefore, it would be desirable to design estimation procedures for fuzzy linguistic preference relations based on the additive consistency property. In [16], a first approach for the case of ordinal fuzzy linguistic preference relations based on the additive consistency property was proposed. However, it fails to use all the estimation possibilities that can be derived from the additive consistency property.

The aim of this paper is to present a complete procedure to estimate missing information in the case of incomplete fuzzy linguistic preference relations. It is based on the linguistic extension of Tanino's consistency principle and makes use of all the estimation possibilities that derive from it. We assume fuzzy linguistic preference relations assessed on a 2-tuple fuzzy linguistic modelling [6] because it provides some advantages with respect to the ordinal fuzzy linguistic modelling [7]. We design a selection process for GDM problems with incomplete fuzzy linguistic preference relations following the choice scheme proposed in [2], i.e., *aggregation* followed by *exploitation*. In this selection procedure we include a new step devoted to complete the fuzzy linguistic preference relations. We also analyse and discuss the use of this estimation procedure of 2-tuple linguistic missing values.

In order to do this, the paper is set out as follows. In Section 2, we present the preliminaries, that is, the concepts of incomplete 2-tuple fuzzy linguistic preference relation and linguistic additive consistency property. Section 3 introduces the complete estimation procedure of missing values for incomplete 2-tuple fuzzy linguistic preference relations. In Section 4, the selection process with incomplete 2-tuple fuzzy linguistic preference relations is presented. In Section 5 we discuss the use of our estimation procedure in the decision process. Finally, in Section 6 we draw our conclusions.

2. Preliminaries

In this section we present the concepts of incomplete 2-tuple fuzzy linguistic preference relation and linguistic additive consistency property.

2.1. Incomplete 2-tuple fuzzy linguistic preference relations

There may be problems that present qualitative aspects that are complex to assess by means of precise and exact values, and therefore linguistic assessments could be used instead [4, 20] to obtain a better solution. In this paper, we use the 2-tuple fuzzy linguistic model [6] to represent experts' preferences. Many advantages of this representation model to manage linguistic information models were given in [7].

The 2-tuple fuzzy linguistic model is based on the concept of symbolic translation and represents the linguistic information by means of a pair of values, (s, α), where s is a linguistic term and α is a numeric value representing the symbolic translation.

Definition 1. *Let $\beta \in [0, g]$ be the result of an aggregation of the indexes of a set of labels assessed in a linguistic term set $S = \{s_0, s_1, \ldots, s_{g-1}, s_g\}$, i.e., the result of a symbolic aggregation operation. Let $i = round(\beta)$ and $\alpha = \beta - i$ be two values, such that, $i \in [0, g]$ and $\alpha \in [-0.5, 0.5)$, then α is called a symbolic translation.*

This model defines a set of transformation functions to manage the linguistic information expressed by linguistic 2-tuples.

Definition 2. *Let S be a linguistic term set and $\beta \in [0, g]$ a value supporting the result of a symbolic aggregation operation, then the 2-tuple that expresses the equivalent information to β is obtained with the following function:*

$$\begin{array}{ll} \Delta: & [0, g] \longrightarrow S \times [-0.5, 0.5) \\ & \Delta(\beta) = (s_i, \alpha) \\ & i = round(\beta) \\ & \alpha = \beta - i \end{array} \quad (1)$$

where "round" is the usual round operation, s_i has the closest index label to "β" and "α" is the value of the symbolic translation.

Proposition 1. *Let $S = \{s_0, \dots, s_g\}$ be a linguistic term set and (s_i, α) be a linguistic 2-tuple. There is always a function, Δ^{-1}, such that from a 2-tuple value it returns its equivalent numerical value $\beta \in [0, g] \subset \mathbb{R}$:*

$$\begin{array}{c} \Delta^{-1} : S \times [-0.5, 0.5) \longrightarrow [0, g] \\ \Delta^{-1}(s_i, \alpha) = i + \alpha = \beta \end{array} \quad (2)$$

A linguistic term can be seen as a linguistic 2-tuple by adding to it the value 0 as symbolic translation, $s_i \in S \equiv (s_i, 0)$, and therefore, this linguistic model can be used to represent linguistic preference relations:

Definition 3. *A 2-tuple linguistic preference relation P on a set of alternatives X is a set of 2-tuples on the product set $X \times X$, i.e., it is characterized by a membership function*

$$\mu_P : X \times X \longrightarrow S \times [-0.5, 0.5) \quad (3)$$

When cardinality of X is small, the preference relation may be conveniently represented by a $n \times n$ matrix $P = (p_{ij})$, being $p_{ij} = \mu_P(x_i, x_j)$ $\forall i, j \in \{1, \dots, n\}$ and $p_{ij} \in S \times [-0.5, 0.5)$.

As aforementioned, missing information is a problem that needs to be addressed. In order to model these situations, in the following definitions we express the concept of an incomplete 2-tuple fuzzy linguistic preference relation:

Definition 4. *A function $f : X \to Y$ is* partial *when not every element in the set X necessarily maps to an element in the set Y. When every element from the set X maps to one element of the set Y then we have a* total *function.*

Definition 5. *A 2-tuple fuzzy linguistic preference relation P on a set of alternatives X with a* partial *membership function is an incomplete 2-tuple fuzzy linguistic preference relation.*

2.2. Linguistic additive consistency

The previous definition of a 2-tuple fuzzy linguistic preference relation does not imply any kind of consistency property. In fact, preference values of a preference relation can be contradictory. Obviously, an inconsistent source of information is not as useful as a consistent one, and thus, it would be quite important to be able to *measure* the consistency of the information provided by experts for a particular problem.

Consistency is usually characterized by *transitivity.* Transitivity seems like a reasonable criterion of coherence for an individual's preferences: if x is preferred to y and y is preferred to z, common sense suggests that x should be preferred to z. As shown in [8], additive transitivity for fuzzy preference relations can be seen as the parallel concept of Saaty's consistency property for multiplicative preference relations [13]. The mathematical formulation of the additive transitivity was given by Tanino in [14]:

$$(p_{ij} - 0{,}5) + (p_{jk} - 0{,}5) = (p_{ik} - 0{,}5) \quad (4)$$

Using the transformation functions Δ and Δ^{-1} we define the linguistic additive transitivity property for 2-tuple fuzzy linguistic preference relations as follows:

$$\begin{array}{l} \Delta[(\Delta^{-1}(p_{ij}) - \Delta^{-1}(s_{g/2}, 0)) + \\ (\Delta^{-1}(p_{jk}) - \Delta^{-1}(s_{g/2}, 0))] = \\ \Delta[(\Delta^{-1}(p_{ik}) - \Delta^{-1}(s_{g/2}, 0)] \end{array} \quad (5)$$

As in the case of additive transitivity, the linguistic additive transitivity implies linguistic additive reciprocity. Indeed, because $p_{ii} = (s_{g/2}, 0)$ $\forall i$, if we make $k = i$ in (5) then we have: $\Delta(\Delta^{-1}(p_{ij}) + \Delta^{-1}(p_{ji})) = (s_g, 0)$ $\forall i, j \in \{1, \dots, n\}$.

Expression (5) can be rewritten as:

$$p_{ik} = \Delta(\Delta^{-1}(p_{ij}) + \Delta^{-1}(p_{jk}) - \Delta^{-1}(s_{g/2}, 0)) \quad (6)$$

A 2-tuple fuzzy linguistic preference relation will be considered *"additive consistent"* when for every three options in the problem $x_i, x_j, x_k \in X$ their associated linguistic preference degrees p_{ij}, p_{jk}, p_{ik} fulfil (6).

3. Estimating missing values for incomplete 2-tuple fuzzy linguistic preference relations

In this section we present a consistency based procedure to estimate the missing values of a 2-tuple fuzzy linguistic preference relations.

3.1. Estimating linguistic values based on the linguistic additive consistency

Expressions (5), (6) can be used to estimate a linguistic preference value p_{ik} $(i \neq k)$ using an intermediate alternative x_j in three different ways:

$$(cp_{ik})^{j1} = \Delta(\Delta^{-1}(p_{ij})+\Delta^{-1}(p_{jk})-\Delta^{-1}(s_{g/2},0)) \quad (7)$$

$$(cp_{ik})^{j2} = \Delta(\Delta^{-1}(p_{jk})-\Delta^{-1}(p_{ji})+\Delta^{-1}(s_{g/2},0)) \quad (8)$$

$$(cp_{ik})^{j3} = \Delta(\Delta^{-1}(p_{ij})-\Delta^{-1}(p_{kj})+\Delta^{-1}(s_{g/2},0)) \quad (9)$$

3.2. An estimation procedure of missing values in 2-tuple fuzzy linguistic preference relations

To manage incomplete 2-tuple fuzzy linguistic preference relations, we need to introduce the following sets [9]:

$$A = \{(i,j) \mid i,j \in \{1,\ldots,n\} \ \wedge \ i \neq j\}$$
$$MV = \{(i,j) \in A \mid p_{ij} \ is \ unknown\}$$
$$EV = A \setminus MV$$

where MV is the set of pairs of alternatives whose preference degrees are unknown or missing; EV is the set of pairs of alternatives whose preference degrees are given by the expert. We do not take into account the preference value of one alternative over itself as this is always assumed to be equal to $(s_{g/2},0)$.

Expressions (7), (8) and (9) are used to define an iterative estimation procedure of missing values in an incomplete 2-tuple fuzzy linguistic preference relation according to the following two steps:

A) Elements to be estimated in step h

$$EMV_h = \{(i,k) \in MV \setminus \bigcup_{l=0}^{h-1} EMV_l \mid \exists j \in \{H_{ik}^{h1} \cup H_{ik}^{h2} \cup H_{ik}^{h3}\}\} \quad (10)$$

with

$$H_{ik}^{h1} = \{j \mid (i,j),(j,k) \in \{EV \bigcup_{l=0}^{h-1} EMV_l\}\}$$
$$H_{ik}^{h2} = \{j \mid (j,i),(j,k) \in \{EV \bigcup_{l=0}^{h-1} EMV_l\}\}$$
$$H_{ik}^{h3} = \{j \mid (i,j),(k,j) \in \{EV \bigcup_{l=0}^{h-1} EMV_l\}\}$$

B) Expression to estimate a particular missing value

In iteration h, to estimate a particular value p_{ik} with $(i,k) \in EMV_h$, the application of the following function is proposed:

function estimate_p(i,k)
1) $cp_{ik}^1 = (s_0,0),\ cp_{ik}^2 = (s_0,0),$
$cp_{ik}^3 = (s_0,0),\ \mathcal{K} = 0$

2) $cp_{ik}^1 = \Delta\left(\dfrac{\sum_{j \in H_{ik}^{h1}} \Delta^{-1}(cp_{ik}^{j1})}{\# H_{ik}^{h1}}\right),\ \mathcal{K}++$
$if\ H_{ik}^{h1} \neq \emptyset.$

3) $cp_{ik}^2 = \Delta\left(\dfrac{\sum_{j \in H_{ik}^{h2}} \Delta^{-1}(cp_{ik}^{j2})}{\# H_{ik}^{h2}}\right),\ \mathcal{K}++$
$if\ H_{ik}^{h2} \neq \emptyset.$

4) $cp_{ik}^3 = \Delta\left(\dfrac{\sum_{j \in H_{ik}^{h3}} \Delta^{-1}(cp_{ik}^{j3})}{\# H_{ik}^{h3}}\right),\ \mathcal{K}++$
$if\ H_{ik}^{h3} \neq \emptyset.$

5) Calculate $cp_{ik} =$
$\Delta\left(\dfrac{1}{\mathcal{K}}\left(\Delta^{-1}(cp_{ik}^1) + \Delta^{-1}(cp_{ik}^2) + \Delta^{-1}(cp_{ik}^3)\right)\right)$

end function

Summarizing, the *iterative estimation procedure* of missing values for incomplete 2-tuple fuzzy linguistic preference relations is as follows:

ITERATIVE ESTIMATION PROCEDURE

0. $EMV_0 = \emptyset$
1. $h = 1$
2. while $EMV_h \neq \emptyset$ {
3.   for every $(i,k) \in EMV_h$ {
4.   estimate_p(i,k)
5.   }
6. $h++$
7. }

Finally, the following proposition provides a sufficient condition that guarantees the success of this estimation procedure [9]:

Proposition 2. *An incomplete 2-tuple fuzzy linguistic preference relation can be completed if a set of $n-1$ non-leading diagonal preference, where each one of the alternatives is compared at least once, is known.*

4. A selection process for GDM with incomplete 2-tuple fuzzy linguistic preference relations

The goal of the selection process in GDM is to choose the best alternatives according to the opinions provided by the experts. A classical selection process consists of two different phases: *aggregation* and *exploitation* (figure 1). Assuming preference relations to represent the experts' opinions, the former defines a collective preference relation indicating the global preference between every ordered pair of alternatives, while the latter transforms the global information about the alternatives into a global ranking of them to identity the best alternatives or the solution set of alternatives.

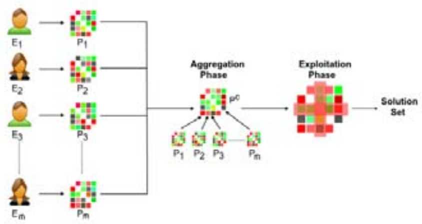

Figura 1: Classical Selection Process

However, there may be cases in which the above classical selection procedure could not be applied satisfactorily when we deal with GDM situations with incomplete preference relations. For instance, some preference degrees of the collective preference relation cannot be computed in the aggregation phase and consequently, the ordering of some alternatives

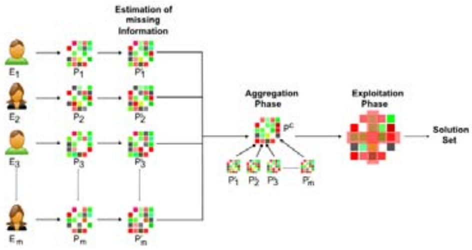

Figura 2: Presented Selection Process

cannot be computed in the exploitation phase. To overcome this problem, we present a selection process for GDM with incomplete 2-tuple fuzzy linguistic preference relations that requires three phases (see figure 2):

1) *Estimation of missing information.* Each incomplete 2-tuple fuzzy linguistic preference relation is completed using the estimation procedure presented in Section 3.

2) *Aggregation phase: The Collective 2-tuple Linguistic Preference Relation.* Once all the missing values in every incomplete 2-tuple fuzzy linguistic preference relation have been estimated, we have a set of m individual 2-tuple fuzzy linguistic preference relations $\{P^1, \ldots, P^m\}$. From this set a collective 2-tuple fuzzy linguistic preference relation $P^c = (p^c_{ik})$ must be obtained by means of an aggregation procedure. In this case, each value $p^c_{ik} \in S \times [-0.5, 0.5)$ will represent the preference of alternative x_i over alternative x_k according to the majority of the most consistent experts' opinions. To obtain P^c we define the following 2-tuple linguistic OWA operator:

Definition 6: A 2-tuple linguistic OWA operator of dimension n is a function $\phi : (S \times [-0.5, 0.5))^n \longrightarrow S \times [-0.5, 0.5)$, that has a weighting vector associated with it, $W = (w_1, \ldots, w_n)$, with $w_i \in [0,1]$, $\sum_{i=1}^n w_i = 1$, and it is defined according to the following expression:

$$\phi_W(p_1, \ldots, p_n) = \Delta(\sum_{i=1}^{n} w_i \cdot \Delta^{-1}(p_{\sigma(i)})) \tag{11}$$

where $p_i \in S \times [-0.5, 0.5)$ and being $\sigma : \{1, \ldots, n\} \longrightarrow \{1, \ldots, n\}$ a permutation defined on 2-tuple linguistic values, such that $p_{\sigma(i)} \geq p_{\sigma(i+1)}$, $\forall i = 1, \ldots, n-1$, i.e., $p_{\sigma(i)}$ is the i-highest 2-tuple linguistic value in the set $\{p_1, \ldots, p_n\}$; and being the comparison of two 2-tuple linguistic values (s_k, α_1) and (s_l, α_2) defined as [6]:

- if $k < l$ then (s_k, α_1) is smaller than (s_l, α_2)
- if $k = l$ then
  1. if $\alpha_1 = \alpha_2$ then (s_k, α_1), (s_l, α_2) represent the same information
  2. if $\alpha_1 < \alpha_2$ then (s_k, α_1) is smaller than (s_l, α_2)
  3. if $\alpha_1 > \alpha_2$ then (s_k, α_1) is bigger than (s_l, α_2)

A natural question in the definition of OWA operators is how to obtain W. In [12] it was defined an expression to obtain W that allows to represent the concept of fuzzy majority [10] by means of a fuzzy linguistic non-decreasing quantifier Q [21]:

$$w_i = Q(i/n) - Q((i-1)/n), \quad i = 1, \ldots, n. \tag{12}$$

Therefore, the collective 2-tuple fuzzy linguistic preference relation could be obtained as follows:

$$p_{ik}^c = \phi_Q(p_{ik}^1, \ldots, p_{ik}^m) \tag{13}$$

where Q is the fuzzy quantifier used to implement the fuzzy majority concept.

3) *Exploitation: Choosing the Solution Set.* In order to select the solution set of alternatives from the collective 2-tuple fuzzy linguistic preference relation we define two quantifier guided choice degrees of alternatives [4], a dominance and a non-dominance degree.

1. $QGDD_i$: The quantifier guided dominance degree quantifies the dominance that one alternative has over all the others in a fuzzy majority sense and is defined as follows:

$$QGDD_i = \phi_Q(p_{i1}^c, \ldots, p_{i(i-1)}^c, p_{i(i+1)}^c, \ldots, p_{in}^c) \tag{14}$$

This measure allows us to define the set of non-dominated alternatives with maximum linguistic dominance degree:

$$X^{QGDD} = \{x_i \in X \mid QGDD_i = sup_{x_j \in X} QGDD_j\} \tag{15}$$

To calculate $sup_{x_j \in X} QGDD_j$ the 2-tuple linguistic comparison operator is used.

2. $QGNDD_i$: The quantifier guided non-dominance degree gives the degree in which each alternative is not dominated by a fuzzy majority of the remaining alternatives. Its expression being:

$$QGNDD_i = \phi_Q(Neg(p_{1i}^s), \ldots, Neg(p_{(i-1)i}^s), Neg(p_{(i+1)i}^s), \ldots, Neg(p_{ni}^s)) \tag{16}$$

where

$$p_{ij}^s = \begin{cases} (s_0, 0) & \text{if } p_{ij} < p_{ji} \\ \Delta(\Delta^{-1}(p_{ij}) - \Delta^{-1}(p_{ji})) & \text{if } p_{ij} \geq p_{ji} \end{cases}$$

represents the degree in which x_i is strictly dominated by x_j, and Neg is the negation operator for 2-tuple linguistic information defined as [6] $Neg(p_{ki}^s) = \Delta(g - \Delta^{-1}(p_{ki}^s))$. The set of non-dominated alternatives with maximum linguistic non-dominance degree is

$$X^{QGNDD} = \{x_i \in X \mid QGNDD_i = sup_{x_j \in X} QGNDD_j\} \tag{17}$$

5. Discussion

In this section, we analyze some important aspects of the use of our estimation procedure within the decision process. To do so, we compare our model with others models and show the advantages of its use in decision making processes.

1. *Comparison with Xu's model [16].* Proposition 2 establishes the minimum condition of our estimation procedure to solve all possibilities of incomplete information when dealing with individual linguistic

preference relations. However, Xu's model [16] does not satisfy that proposition. Then it could not solve all possibilities of incomplete information because it does not use all estimation possibilities that can be derived from Tanino's consistency property. It makes use only of the equation (7), and do not take into account the other two equations (8), (9). Thus, if we have the following incomplete 2-tuple fuzzy linguistic preference relation

$$P = \begin{pmatrix} - & x & (W,0) & x \\ x & - & (E,0) & x \\ x & x & - & x \\ x & x & (MB,0) & - \end{pmatrix}$$

our procedure obtains the following 2-tuple fuzzy linguistic preference relation

$$\begin{pmatrix} - & (W,0) & (W,0) & (N,0) \\ (B,0) & - & (E,0) & (MW,0) \\ (B,0) & (E,0) & - & (MW,0) \\ (T,0) & (MB,0) & (MB,0) & - \end{pmatrix}$$

while Xu's model would not be able to obtain any missing value because there is not any intermediate alternative x_j for which equation (7) can be applied, therefore, the complete 2-tuple fuzzy linguistic preference relation could not be calculated.

2. *On the choice degrees in the selection process.* Given an incomplete fuzzy linguistic preference relation, the selection process could not be carried out because the choice degrees could not be obtained. For example, in the following incomplete fuzzy linguistic preference relation

$$P = \begin{pmatrix} - & W & x & x \\ x & - & x & x \\ x & MW & - & x \\ E & MW & x & - \end{pmatrix}$$

we cannot obtain neither QGDD nor QGNDD for all alternatives. On the one hand, the quantifier guided dominance degree cannot be obtained because there are no values in the second row. On the other hand, matrix P^s is not possible to be calculated because there are missing values on the linguistic preference, and therefore neither the quantifier guided non-dominance degree can be calculated. However, if our procedure is used, we are able to obtain both QGDD and QGNDD.

3. *In the selection process.* If experts provided incomplete fuzzy linguistic preference relations, the aggregation phase might not be possible to be carried out to obtain a complete collective 2-tuple linguistic preference and therefore, as we have aforementioned, the choice degrees could not be applied. For example, if three experts provide the following incomplete fuzzy linguistic preference relations

$$P^1 = \begin{pmatrix} - & x & (W,0) & x \\ x & - & (E,0) & x \\ x & x & - & x \\ x & x & (MB,0) & - \end{pmatrix}$$

$$P^2 = \begin{pmatrix} - & x & (B,0) & x \\ x & - & (B,0) & x \\ x & x & - & x \\ x & x & (MW,0) & - \end{pmatrix}$$

$$P^3 = \begin{pmatrix} - & x & (MW,0) & x \\ x & - & (T,0) & x \\ x & x & - & x \\ x & x & (B,0) & - \end{pmatrix}$$

then only the collective values p^c_{13}, p^c_{23} and p^c_{43} could be obtained and therefore, the selection process could not be applied satisfactorily.

6. Conclusions

In this paper we have proposed an additive consistency based procedure to estimate missing values in incomplete 2-tuple fuzzy linguistic preference relations. It is able to be applied in situations where other consistency based linguistic approaches are not. Additionally, we have shown its application in a selection procedure of its advantages with regards to previous procedures.

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