Modelling twofold uncertainty in the condition assessment of residential buildings using interval valued fuzzy signatures

Ádám Bukovics
Department of Structural and Geotechnical Engineering
Széchenyi István University
Győr, Hungary
bukovics@sze.hu

István Á. Harmati
Department of Mathematics and Computational Sciences
Széchenyi István University
Győr, Hungary
harmati@sze.hu

László T. Kóczy
Department of Automation
Széchenyi István University
Győr, Hungary
koczy@sze.hu
Department of Telecommunications and Media Informatics
Budapest University of Technology and Economics
Budapest, Hungary
koczy@tmit.bme.hu

***Abstract*—In this study we will describe an intervention decision-support method related to residential buildings, which is modelling the condition of buildings based on linguistic expert opinions so that it is capable of taking into consideration the uncertainties included in the expert opinions. Fuzzy signature-based model is used, wherein the uncertainties are integrated into the system by applying interval valued fuzzy sets, as well as linguistic hedges. The result will be a fuzzy set for each building, describing the condition of the whole building, specify the bourdary values between which the condition of the building may fall.**

***Keywords*—interval valued fuzzy signature; type-2 method; membership function; residential building; assessment**

I. Introduction

In order to provide for the continous maintenance of residential buildings and keep up the level of the condition of structures there must be completed status retaining and structure renewing works on buildings in case of justified building structures at the right time and in the reasonable extent.

To support it there are often expert opinions available, which are analysing the structural system and condition of the buildings (the structural deteriorations and occasionally the reasons triggering those) in details. Processing the expert opinions there can be a database created based on which we have developed a status evaluating and ranking model, which provides an intervention decision-support. Since partly due to subjective and objective reasons the expert opinions may contain many uncertainties and incorrectness, such uncertainties must also be taken into account when preparing the model.

In the course of our study we have developed a fuzzy signature based model wherein modelling of uncertainties were completed by using interval valued fuzzy set as well as linguistic hedges.

II. Short discription of fuzzy signatures and type-2 fuzzy signatures

A. Fuzzy signatures

In many fields of science and technology arise problems of modelling complex systems, but usually the exact mathematical model is not known or too difficult to deal with, due to lack of detailed knowledge of the parameters or the behavior of the system. Moreover, lack of reproducibility and not well-defined interdependencies between the variables are also common features.

Fuzzy signatures are useful tools in modelling such complex systems and objects. In this kind of approach, the complex systems is described by a set of qualitative measures, which are also arranged into a hierarchical framework expressing interconnections and dependencies, and modelling the human approach to the problem.

In the literature there is a wide variety of applications, for example in economy, in the medical field, and in several fields of engineering and informatics, for example robotics, data mining and civil engineering.

The complex system is described by a set of qualitative measures, which are also arranged into a hierarchical framework expressing interconnections and dependencies, and modelling the human approach to the problem. In mathematical point of view, fuzzy signatures are hierarchical representations of data structured into vectors of fuzzy values. A fuzzy signature can be represented by a nested vector value fuzzy set or by a tree graph with fuzzy memberships at the leaves.

B. *Type-2 fuzzy signatures*

Here the inputs of the signature are fuzzy sets $A_1, A_2, \ldots, A_n$ representing the uncertainty of the input membership grades, so their supports are subsets of the [0,1] interval (Fig. 1). The output is a fuzzy set representing the uncertainty of the final membership grade. The output fuzzy set is computed from the inputs by appropriate extension of the aggregation operators to fuzzy sets. For extension of the operations to fuzzy sets we use Zadeh's extension principle.

III. SETUP OF THE MODEL

With modelling the status of residential buildings the components are well structured and thus a hierarchical tree-structure can be built up from them. So we can win significant additional information about the problem. In this study a four-level fuzzy signature structure was used.

At a higher level some components of the tree structure are specified by a partial tree of the components. At the peaks of the structure the basic set of the interval valued fuzzy sets should be within the interval of [0,1].

The interval valued fuzzy sets at the peaks of the structure are related to the following building structures: foundation structures (A_1), wall structures (A_2), cellar floor (A_3), intermediate floor (A_4), cover floor (A_5), side corridor structures (A_6), step structures (A_7), roof structures (A_8), roof covering (A_9), facade (A_{10}), footing (A_{11}), tin structures (A_{12}), insulation against soil moisture and ground water (A_{13}) (Fig. 1). These interval valued fuzzy sets describe the status of the examined building structures, as defined by experts and the uncertainties and inaccuracies too.

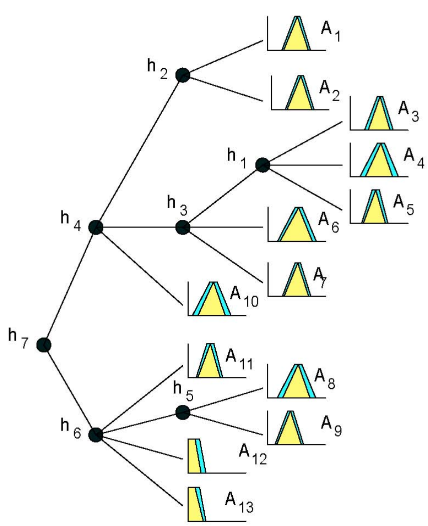

Fig. 1. Type-2 fuzzy signature

With the use of the aggregation operators we can modify the structure of the fuzzy signatures. In such a case a sub-tree of the variables is reduced to the root of the sub-tree. One of the recursive processes of the model can be seen on Fig. 2. With the use of the aggregation operators the aggregated values from a set of values at the lower level nodes are calculating.

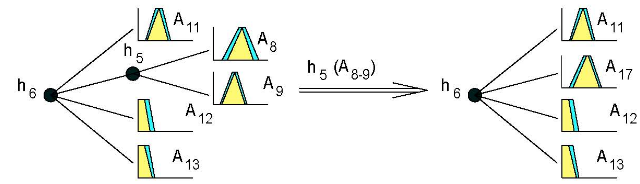

Fig. 2. Recursive process

The applied aggregation operators are weighted mean operators. These depend on the special features of the building (extend of cellar (*m*), side corridor (*f*), number of storeys of the building (*n*)) and the relevance weight of the building structures.. For example the h2 aggregation operator, related to the condition of vertical load bearing structures and the h3 aggregation operator related to the condition of the horizontal load bearing structures were defined as follows.

$$\mathrm{h}_2 = (0.50 - 0.05 \cdot (n-1)) \cdot A_1 + (0.50 + 0.05 \cdot (n-1)) \cdot A_2 \tag{1}$$

$$\mathrm{h}_3 = \frac{0.65 \cdot h_1 + 0.20 \cdot f \cdot A_6 + 0.15 \cdot A_7}{0.80 + 0.20 \cdot f} \tag{2}$$

IV. STEPS OF MODELLING THE MEMBERSHIP FUNCTIONS WHICH ARE AT THE LEAVES

The expert specifies the condition of the examined building structures with a linguistic description and in many cases with a discrete value. Hereinafter some short examples will demonstrate the linguistic description which shows the uncertainties thereof:

"Large deformation of roof-covering on the side of courtyard, beams are bent upwards, trimmers are slackened. Current stability of roof-structure is doubtful, the structure is hardly acceptable. Roof-covering can be made acceptable by repair (fixing)."

„Thin cracks can be seen on the lower plane of floor in the line of steel beams, the structure is still acceptable."

„Very wet, basalt wall material weathered, lime mortar corroded. Solidity approximately: TF5. Acceptable." In order to get fuzzy sets from these data, in the first step the condition of every examined building structure must be characterised by a linguistic label. When determining the number of linguistic labels it was taken into account to choose such a classification system which is well-known and can be confidently used by the experts, and it was also a viewpoint to have odd number of linguistic labels. We have used a scale containing altogether 5 linguistic labels (*very bad condition, bad condition, average condition, good condition, excellent condition*).

Since the linguistic label specified by the expert is not a discrete value (there can be significant difference between the condition of two building structures evaluated by the same linguistic label), therefore three membership functions are assigned to each linguistic label. In case of internal linguistic labels (C2, C3, C4) we used triangular-shaped membership function, while in extreme cases (C1, C5) trapezoidal-shaped membership function is used (step 1). Thus the transition between two linguistic variables can be modelled in a much more sophisticated manner (Fig. 3).

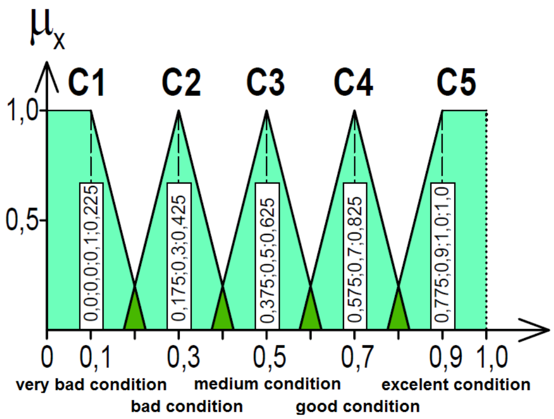

Fig. 3. The initial membership functions

Within the 5 linguistic labels there is a possibility to further differentiate the conditions, by which the condition of structures can be more precisely modelled from verbal evaluations of expert opinions and from other additional information.

By using the linguistic hedges each membership function (C1-C5) can take 3 different shapes, thus altogether 15 linguistic labels are available to determine the condition of building structures.

If we would like to modify the membership function which belongs to the linguistic label of „good condition", there are 3 new linguistic labels available (C4/1: disadvantageous direction (closer to medium condition), C4/2: stable, C4/3 : advantageous direction (closer to excellent condition)

Since the experts are evaluating the condition of structures in two steps, in the well-known classification system, they can more confidently and more precisely define the conditions than in case they were provided a scale including 15 or 20 linguistic labels in one step.

The applied linguistic hedges modify the membership function in the following way. The triangular membership functions are represented by the triple (a,b,c), while the trapezoidal membership functions are represented by the quadruple (a,b,c,d).

Step 2:
C1: (a,b,c,d) → (a,b,c',d')
C2,C3,C4: (a,b,c) → (a,b',c)
C5: (a,b,c,d) → (a',b',c,d)

The 15 membership functions obtained in this manner can be seen on Fig. 4.

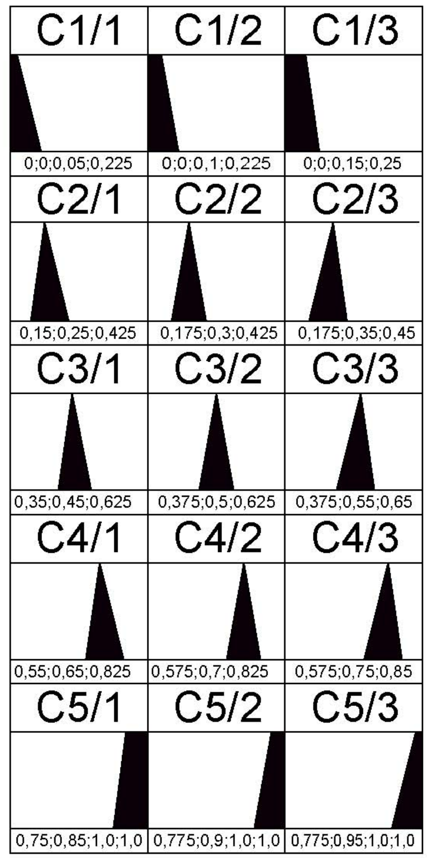

Fig. 4. Further differentiating the conditions by using linguistic hedges

In the following step the membership functions are transformed into interval valued fuzzy sets.

Thus partly the uncertainty is modelled how precisely the expert could observe the examined structure, what quantity of information was available for the expert and whether the observations were direct or indirect based on which the status of the structure could be concluded. At this point that uncertainty is taken into account that it is often difficult to characterise the linguistic description included in the expert opinion with any linguistic label (UC1: slight uncertainty, UC2: medium uncertainty, UC3: slight uncertainty)

The applied linguistic hedges modify the membership function in the following way:

Step 3 (with the modified membership functions):

lower:
(a,b,c) → (a+e1,b,c-e1)
where the possible values of e1 are 0.015, 0.03 and 0.045.
upper:
(a,b,c) → (a-e2,b-e2,b+e2,c+e2) where the possible values of e2 are 0.05, 0.1 and 0.15.

for C1:
lower:
(a,b,c,d) → (a,b,c-e1,d-e1)
upper:
(a,b,c,d) → (a,b,c+e2,d+e2)

for C5:
lower:
(a,b,c,d) → (a+e1,b+e1,c,d)
upper:
(a,b,c,d) → (a-e2,b-e2,c,d)

If the modification yields a value lower than zero (or greater than one), then this value will be replaced by 0.

The transformation of the membership function can be seen on Fig. 5.

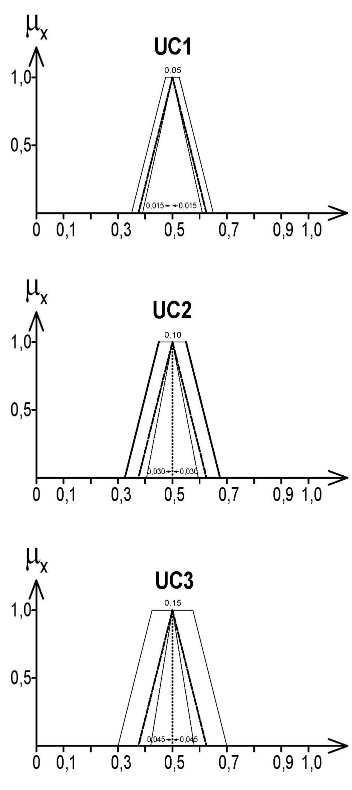

Fig. 5. Transforming the membership function into interval valued fuzzy sets

Professional experience and skill of the expert who prepares the expert opinion can be achieved by further modification of the fuzzy set (EE1: less expert experience, EE2: significant expert experience, EE3: very significant expert experience).
The applied linguistic hedges modify the membership function in the following way:

Step 4 (with the modified membership functions which are already trapezoidal membership functions):

lower: remains the previous

upper:
(a,b,c,d) → (a,b-e3,c+e3,d) where the possible values of e3 are 0, 0.02 and 0.4.

The transformation of the membership function can be seen on Fig. 6.

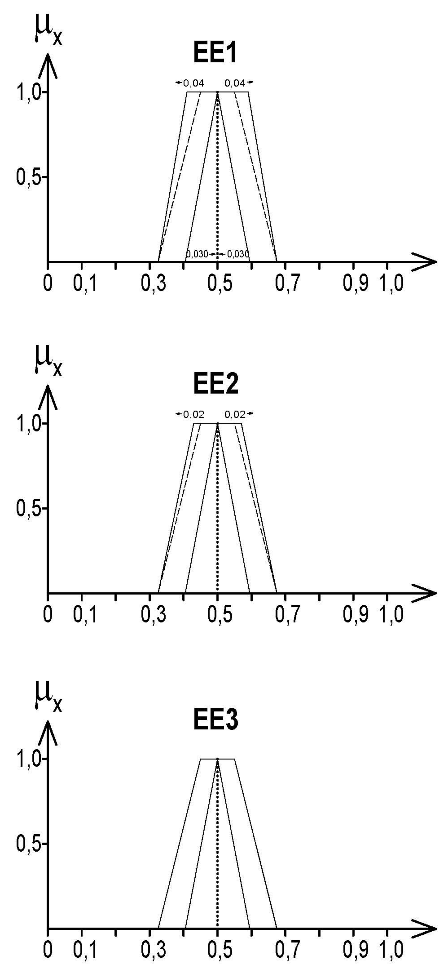

Fig. 6. Modifying the shape of the interval valued fuzzy set

These modified fuzzy sets are used on the peaks of fuzzy signature for modelling the condition of each examined building structure.

V. TESTING THE MODEL

With the aim of examining the structural system, deteriorations of residential buildings and their main reasons, formerly we have analysed detailed status examination expert opinions of more than 300 residential buildings.

Based on the analysis a database was created which included all relevant data and characteristics of the examined residential buildings.

This database is used for testing the model. The advantage is that the reliability of the model can be tested on real buildings, and the achieved results can be analysed based on existing buildings and real expert opinions.

We have chosen 4 residential buildings for testing the model. The first residential building was built in 1832, it is a three-storey building having cellar underneath, flats can be accessed typically through side corridors. The second examined building was built in 1941. It is a four-storey building with side corridor and cellar underneath. The third building was built in 1944, it is a two-storey building with side corridor and cellar underneath, and fourth building was built in 1908, which is a two-storey building with side corridor and also with cellar underneath.

On Fig. 7 it can be seen how the linguistic description provided by the expert is transformed into membership functions, then the way how the uncertainties and additional information are taken into consideration by using linguistic hedges and interval valued fuzzy sets:

Related to the third and fourth examined buildings on Fig. 8 interval valued fuzzy sets can be seen, modelling the condition of the 13 examined building structures – and also including the uncertainties.

Having run the model every examined building can be characterised by an interval valued fuzzy set (Fig. 9). The input fuzzy sets were triangular and trapezoidal fuzzy sets. The output fuzzy sets, which represent the uncertainty of the final membership value are trapezoidal fuzzy sets.

The output has two parts: the lower and the upper membership function, representing the lower and upper bound of the uncertain membership grade. The fuzzy set demonstrates the values between which the condition of the building may fall.

If needed, interval valued fuzzy sets can be transformed into linguistic labels with a defuzzification method.

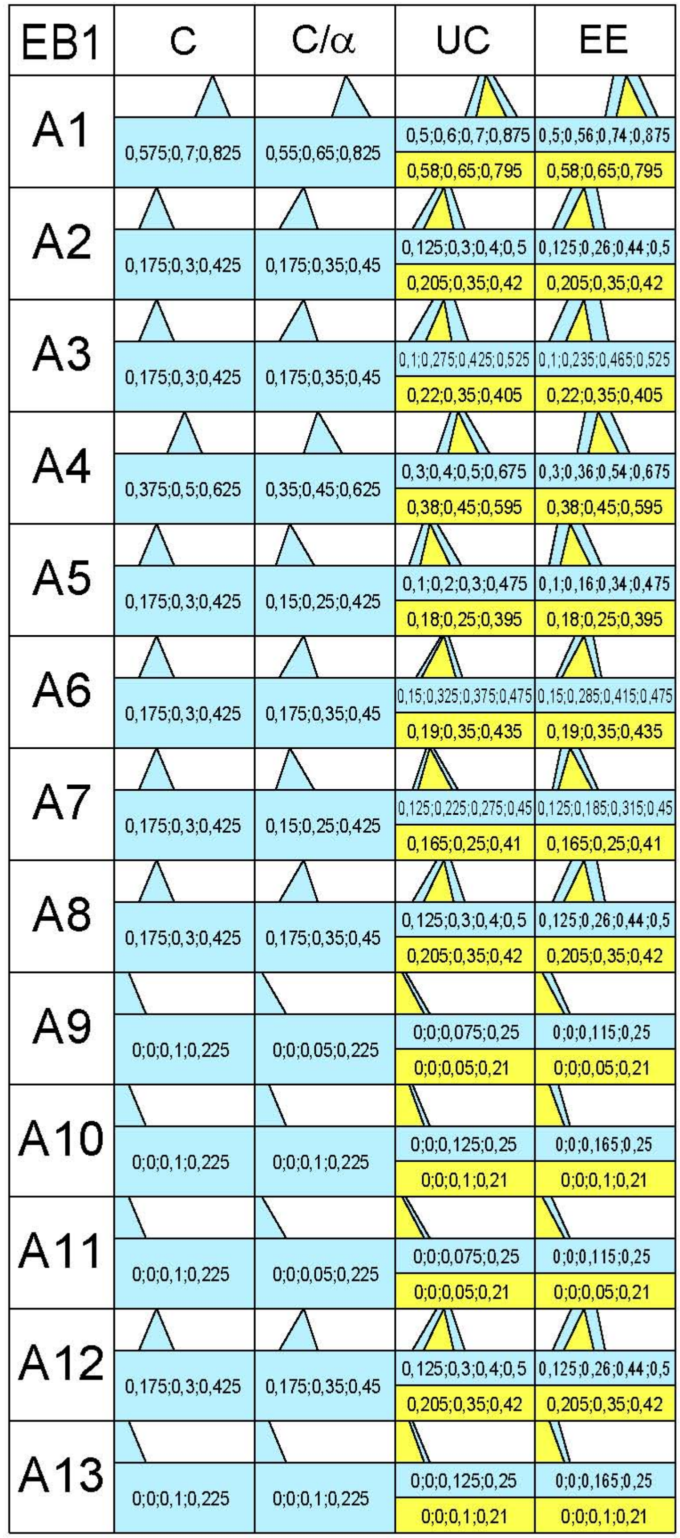

Fig. 7. Modification of fuzzy sets

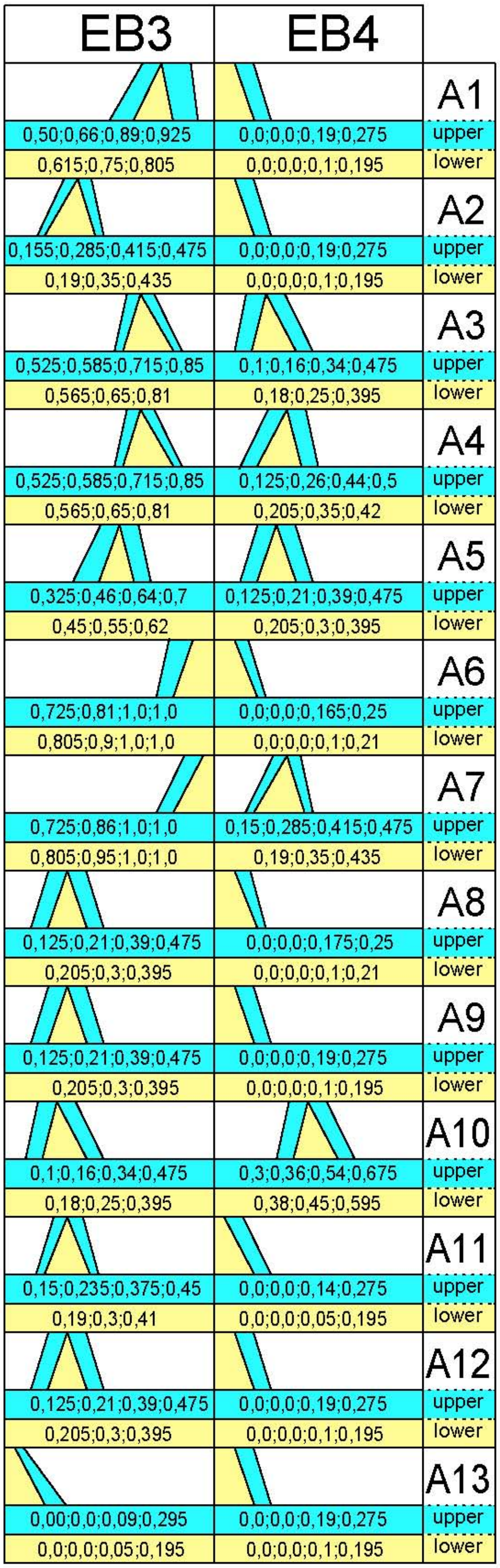

Fig. 8. Interval valued fuzzy setsincluding the uncertainties

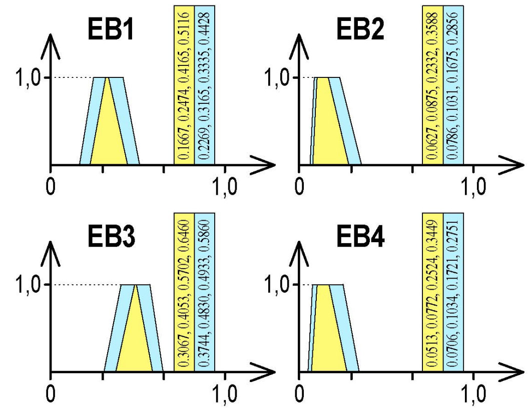

Fig. 9. The final interval valued fuzzy sets of the tested buildings

VI. Summary

Condition of residential buildings can be modelled with appropriate accuracy by a fuzzy signature based model, so that the condition of examined building structures are specified by triangular-shaped fuzzy membership functions on the peaks of the structure. We can also model the uncertainties and inaccuracies in the course of preparing the expert opinions occurring because of the preparedness and subjectivity of the expert, by using linguistic hedges and interval valued fuzzy sets. With the help of interval valued fuzzy sets it can also be modelled, that verbal values cannot be unambiguously transformed into a numerical value. This method can help carry out optimum allocation of economic resources that can be used for the renewal (rehabilitation) of residential buildings.

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