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Fuzzy Rule Interpolation Based Fuzzy Signature Structure in Building Condition Evaluation

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Abstract— **The complexity of the residential house structures makes their condition evaluation difficult. Taking the human experts' thinking into consideration the linguistic approach seems reasonable, therefore the fuzzy set theory may provide a basis for creating an expert system. In practice, the assessment of some predefined attributes of building components may give a comprehensive value about the condition of the examined building on a relative scale. The data structure of building evaluation procedure makes clear that the fuzzy signature structure is helpful in analysis. The numerous building components that determine the character of the given building can turn to an unnecessarily large rule-base. The fuzzy rule interpolation and the corresponding sparse fuzzy rule-based knowledge representation could be a reasonably efficient structure for handling the building evaluation procedure.**

In this paper the fuzzy rule interpolation as a novel aggregation method in fuzzy signature structures is proposed. Its application is presented with a case study of roof structure evaluation of a classic urban-type residential house located in a historic district of Budapest, Hungary.

I. Introduction

DUE TO THE CLIMATE CHANGE and the enactment of the concept of sustainable building, the refurbishment of existing built environment has come to the focus in Budapest, Hungary. The urban structure of the historic districts consists of old residential buildings mainly that were built before WW2; around 27% of present apartments are located in more than 90 years old residential houses [1]. In general, it is ascertainable without any exaggeration that the physical condition of these buildings is, at least, questionable. In the socialism era (1948-1989) almost the life-danger states were eliminated only [2]; instead of maintaining the existing building stock new council estates were developed [3]. As a conclusion of missing or incomplete actions in real estate management the average physical condition of old residential houses became crucial at 1990. The fragmented ownership structure (the capital-scarce former tenants constitute the stakeholders' community at present), and the given physical condition of the residential houses resulted in difficulties in maintenance and in repair nowadays.

II. Difficulties in Building Condition Evaluation

The classic urban-type residential house that symbolizes the glory days of Budapest (1870-1920) was constructed with traditional methods and of traditional building constructions: masonry structures (footing, walls, brick lintels, cellar vault, etc.), experimental reinforced concrete slab systems and side corridors, and pitched roof with wooden framework and ceramic tiling (the Fig. 1. represents a section of a classic style residential house).

In the frame of an ongoing project the determination of the optimum solution in the maintenance process of such residential houses is in the target. In this matter the optimum solution means that the financial capacities of the owners' community have to be taken into consideration, while long-lasting corrections have to be found that can be realized in the shortest repair duration. In addition, the importance of intervention also influences the maintenance schedule. The repair process focuses on the common areas and their building components as they are common property of the owners' community (as it is described in the Stakeholders' Act, in Hungary, 1994).

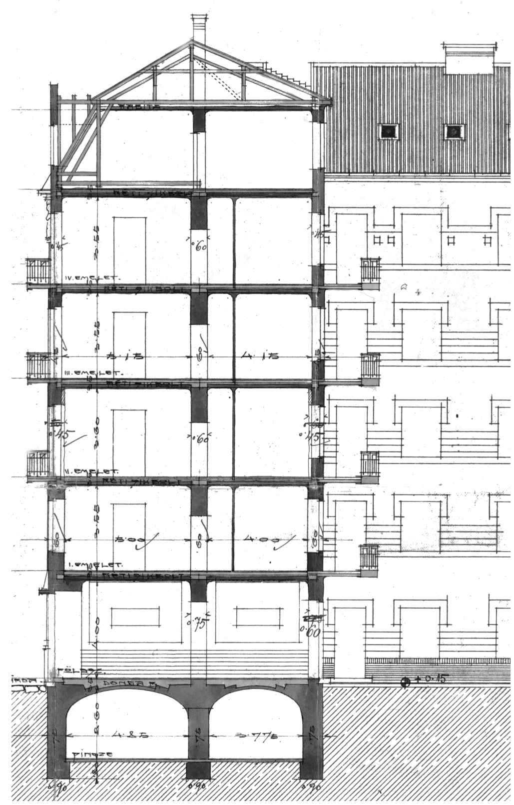

Fig. 1. Section of a classic urban-type residential house (copy of blueprint, 1912; source: Budapest Archives)

As the preliminary step, a complete qualitative condition evaluation of the given residential house has to be prepared for determining the possible maintenance alternatives. As

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usual, visual diagnostic surveys have to be done that evaluate the building and its parts qualitatively, give explanations about deteriorations and recommend repair solutions; and, in special cases, determine further examinations. Several European and National Standards support the experts' activity on site in defining building elements and in failure description. Beside these standards, numerous methods for evaluating building structures exist (from the aspect of the durability and stability of building components [4], [5], [6], service life [7], [8], [9], [10] and energetic performance [11]).

The direct application of suggested evaluation methods raises difficulties in case of subjected building type and its previously mentioned circumstances. Due to the operation complexity of any buildings these methods can be applied for evaluating them individually; therefore the calculations may take needlessly long time. The age of examined building type some methods that focus on life span may produce false results. In addition, these evaluation methods disregard the fact that alternative solutions may be recommended that give different result from the point of performance or aesthetic view [12].

In the last few years the fuzzy signature structures were applied successfully in characterizing such residential buildings [13], [14], since

- numerous, partly hierarchically related attributes describe the physical character of any building;
- the depth and completeness of available surveys are not identical, and the fuzzy signatures make possible to handle data with partially different structures together; and
- the numerous qualitative data that are contained in the surveys justify the application of fuzzy set theory in evaluation.

However, contrary to the previous approach, we propose a novel treatment. Since there is a lot of components at this building type, the rule base characterization results in enormous amount of rules. The attributes of building components are typically continuous, structured, scalable (in its subjective sense), metric and measurable along axes at the same time; therefore the conditions that make the application of sparse rule base and the interpolative calculations on this rule base possible exist. In consequence of this statement, we propose the application of fuzzy rule interpolation method in the building evaluation procedure.

III. Rule Interpolation in Fuzzy Signature Structures

A. Fuzzy Signature Structures

In the way of generalization of fuzzy sets the L-fuzzy sets have to be mentioned that was proposed by Goguen in 1967 [15]. L-fuzzy membership grades are elements of an arbitrary lattice L:

$$A : x \to L \forall x \in X \tag{1}$$

The vector-valued fuzzy sets [16] are special L-fuzzy sets, where L is the lattice of n-dimensional fuzzy vectors, in (1). Vector valued fuzzy sets assign to each element of X a set of quantitative features rather than a single degree this way providing additional information about the specific element.

The formalism of fuzzy signature (Fsig) that supports describing and evaluating hierarchically structured, partly incomplete and vague database was introduced in [17]. Fuzzy signatures are generalized vector valued fuzzy sets, where each vector component is possibly another nested vector. This generalization can be continued recursively to any finite depth, thus forming a signature with depth m.

$$A_s : x \to [a_i]_{i=1}^k, a_i = \begin{cases} [0,1] \\ [a_{ijl}]_i^k = 1 \end{cases}, \forall x \in X \tag{2}$$

The structure of fuzzy signatures can be represented both in vector form and also as a tree graph (Fig.2. represents both the vector form and the tree graph of the fuzzy signature structure).

Fuzzy signatures can be considered as special, multidimensional constructions that are applicable for storing structured fuzzy data. In this structure the dimensions are interrelated in that a sub-group of variables determines a character on a higher level. Therefore, complex and interdependent data components can be described and evaluated in a compact way.

In many applications, the obtained information of experts can be described in different ways, even the structure of observation can be different; nevertheless decisions have to be taken by these data. With the assistance of signatures these alterations in structures can be handled. The main advantage of the application of the fuzzy signatures is that they can handle situations with uneven data structures and information.

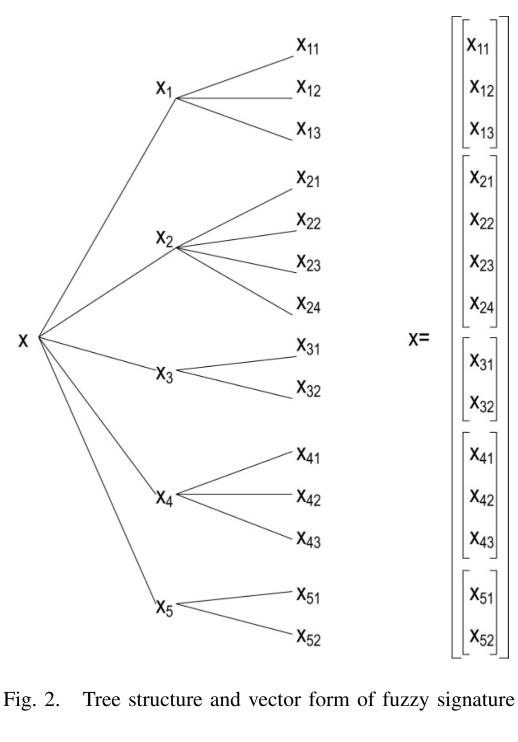

Fig. 2. Tree structure and vector form of fuzzy signature

Furthermore, the model created for the given task can be arranged hierarchically [18]; this feature is very similar to the way of thinking of human experts. This fact underlines the argument that fuzzy signatures are deployable on the area of decision making.

Another advantage of the fuzzy signatures is that they organize the available data components into hierarchical structures. This hierarchy determines the basic structure of fuzzy signature-based observations. It may occur that some elements are missing at several observations. Therefore, it is necessary to employ a structure modifier operator for comparing signatures with quite different structures. It is advisable to apply aggregation operators for reducing sub-trees to their parent node. In case of a multilevelled hierarchy, a recursive process leads to obtaining the aggregated value of the parent node.

In our case, as the most important question the aggregation operators had to be defined. The structure of the fuzzy signature supports the use of different aggregation operators for each node.

B. Aggregation Solutions

For aggregating sub-trees within the fuzzy signatures the WRAO operator (Weighted Relevance Aggregation Operator, was introduced by Mendis et al. [19]. With the application of weighted aggregations more expert knowledge can be involved in the examination. The initiated relevance weight determines the relevancy of a child node on a higher level. For determining the relevance weights by observation Mendis et al. [20] propose a method. A possible application of WRAO was introduced in [21] and [22].

A comprehensive description of other aggregation operators are discussed in [23]; this paper presents original operators on signatures e.g., contraction, extension, pruning, addition, multiplication and grafting; in addition, attractive applications of signatures related to the modelling of fuzzy inference systems are also discussed.

C. Fuzzy Rule Interpolation

Traditional fuzzy rule based systems (e.g. the Zadeh-Mamdani-Larsen CRI ([24], [25], [26]) or the Takagi-Sugeno fuzzy inference ([27], [28]) requires a complete rule base with all of the possible rules set, even though lots of these rules are unimportant from the viewpoint of the actual application. A fuzzy rule base is called sparse or incomplete if an observation may exists, which does not hit any of the rules in the rule base. Accordingly, there can be observations, where no conclusion can be gained with traditional fuzzy reasoning techniques. On the other hand, in many embedded control application areas having no conclusion is an avoidable situation. One real solution for the sparse rule base is the application of fuzzy rule interpolation (FRI) methods. The first fuzzy rule interpolation techniques were introduced in [29]; the comparison of simple interpolation approaches is discussed in [30].

In the case of sparse rule base the derivable rules are intentionally missing from the rule base, as FRI methods are capable of providing reasonable (interpolated) conclusions even if none of the existing rules fire under the current observation. In FRI, the rule base could contain the most significant fuzzy rules alone without risking the chance of having no conclusion for some observations. In this case, having an efficient knowledge representation, a considerable amount of unnecessary work can be avoided during the rule base creation. On the other hand, most FRI methods share the burden of high computational demand, e.g. the task of searching for the two closest surrounding rules to the observation, and calculating the conclusion at least in some characteristic α-cuts. Moreover, in some methods the interpretability of the fuzzy conclusion gained is also not straightforward [31].Lot of effort has been made to rectify the interpretability of the interpolated fuzzy conclusion [32]. In [33] Baranyi et al. give a comprehensive overview of the recent existing FRI methods. Beyond these problems, some of the FRI methods are originally defined for one dimensional input space, and need special extension for the multidimensional case (e.g. [34], [35]). In [36] Wong et al. give a comparative overview of the multidimensional input space capable FRI methods. In [34] Jenei introduces a way for axiomatic treatment of the FRI methods. In [37] Johanyák introduces an automatic way for sparse fuzzy model identification from sample data. The high computational demand, mainly the search for the two closest surrounding rules to an arbitrary observation in the multidimensional antecedent space makes many of these methods hardly suitable for real-time applications. Some FRI methods, (e.g. the method introduced by Jenei et al. In [35] or FRIPOC [38]), eliminate the search for the two closest surrounding rules by taking all the rules into consideration, hence speeding up the reasoning process. On the other hand, keeping the goal of constructing fuzzy conclusion, and not simply speeding up the reasoning process, they still require some additional (or repeated) computational steps for the elements of the level set (or at least some relevant α levels). An application oriented aspect of the FRI, the low computational and resource demand is emerging in the concept of FIVE (Fuzzy Interpolation based on Vague Environment) is introduced in [39].

IV. Attributes of Residential Buildings

The attributes of the total system are determined by numerous components. The values assigned to these components determine the complete character of the given system. In practice, the system, namely an existing building can be separated into constituent elements as building constructions (as it is described above, in this examination the commonly owned building constructions are evaluated only). With the knowledge obtained from technical literature (as [40], [41], etc.), it is clearly visible that these building constructions are sortable into groups by their function and location in the building. Thus the values of building constructions of a group may determine their common value on a higher level together. In some cases, these group may be decomposed into subgroups, therefore the depth of the hierarchy can be different in some segments.

The value is an indicator on a relative scale where the maximum can be reached by the total reproduction of the building with the best constructional and architectural solutions; the minimum is equal to the value of a necessarily abandoned building. It should be underlined that the calculated value as the result of the evaluation is quasi-independent from the market price of the given residential house, since other factors (location, infrastructure, other external circumstances) have much more dominant weights for determining the real estate value of this building.

Four basic attributes of each building component and their groups were chosen that are able to characterize the given component or group together with linguistic categories.

The performance (P) attribute compares the capacity of the given element with the requirements (e.g. load-bearing abilities in case of masonry structures, or waterproofness of damp proof course, etc.). The value of the examined item can be below standard (B_s); standard (S_t) or excellent (E_x).

The estimated life span (LS_E) attribute determines how long the given element can operate in its function approximately without interventions. The linguistic categories are defined as short (S_h); medium (M) and long (L_o).

Contrary to the previous attributes the architectural (or aesthetic) value (AV) is definitely a non-measurable aspect: with its support the relation of the examined element with its environment can be evaluated. Undoubtedly this aspect also plays an important role during a renovation procedure. The categories are low quality (L_q), average (A) and high quality (H_q).

In addition to these attributes, the evaluation should take the reparability into consideration. The attribute called repair difficulties (RD) gives information about the repair costs and the accessibility of the given item. Its linguistic categories are easy (E_a), reasonable (R) and difficult (D). The attributes and their linguistic categories are represented in Table I.

TABLE I
ATTRIBUTES AND THEIR LINGUISTIC CATEGORIES IN EVALUATION PROCEDURE

P	Performance	B_S	below standard
		S_t	standard
		E_x	excellent
LS_E	Estimated Life Span	S_h	short
		M	medium
		L_o	long
AV	Architectral Value	L_q	low quality
		A	average
		H_q	high quality
RD	Repair Difficulties	E_a	easy
		R	reasonable
		D	difficult

The character of the total building (C_{TOT}) is represented by the root of the fuzzy signature hierarchy; it is determined by the value of the load-bearing structure (LB), the roof structure (RS), the basement and plinth ($B\&P$), the side corridor (SC), the entrance hall (EH), the air-shafts (AS), the staircases (S), the mechanics supplies (ME) and the electricity (EL). As it is mentioned above, these groups of building components are decomposable into building elements (e.g. the foundation system and the walls are part of the load-bearing structure, LB). In an elaborative examination, the condition evaluation must focus to the level of building elements, but in some cases, a comprehensive assessment may give more useful result for further analyses.

With the proposed approach the groups of building components are analyzed with the support of the previously mentioned attributes. The properties of building components are easily determinable with the knowledge and information obtained by the concerned literature (e.g. [42]). In this model the attributes (P, LS_E, $\cdots$) represent the leaves that determine the value of the subjected group of building components together on a higher level. The assigned values of the groups (LB, RS, $B\&P$, $\cdots$) result in the value of the examined building (C_{TOT}). The Fig. 3. represents the graph form of the fuzzy signature structure of evaluation data structure.

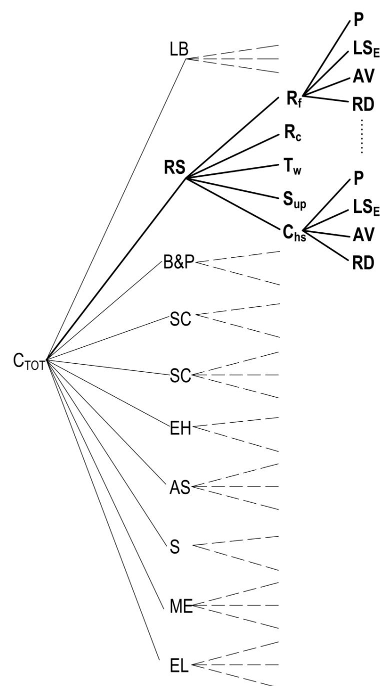

Fig. 3. Signature structure of building evaluation (detail), highlighting the roof structure segment)

V. A Case Study: Evaluation of the Roof Structure

A. Fuzzy Signature Describing the Roof Structure

The sensitivity of the condition evaluation of the building mostly depends on the examination level: in case of examining the building elements the evaluation may give nearly exact values with long-lasting calculation process; on the other hand, the assessment on the level of group of building components results in rough values with fast evaluation process. As an optimum solution the level of sub-groups are recommended for comparatively fast and reliable evaluating.

In this paper, the proposed method is represented in the RS segment (roof structure evaluation) of the entire model. In the given case, the residential building has traditional pitched roof with its customary components. The value of the roof structure (on the top of this segment) is determined by roof framework (R_f), covering (R_c), tinsmith work (T_w), supplementary elements (S_{up}) and chimney shaft (C_{hs}) (the signature structure is represented in Fig 3). The Fig. 4. represents the architectural section of the roof structure and its sub-groups.

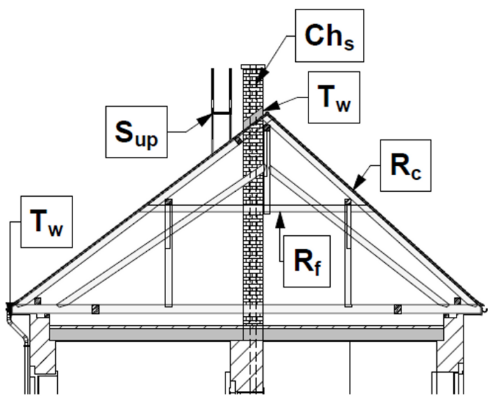

Fig. 4. Overview of roof structure of classic urban-type residential houses. Notes: R_f:roof framework; R_c: roof covering; T_w: tinsmith work; S_{up}:supplementary elements; Ch_s: chimney shaft)

The subgroups of the roof structure can be evaluated with independent attributes that have different categories. The value of a roof framework can be dangerous (D_a), periodic control needed (P_c) or safe (S_a); the roof covering can be weak (W), sensitive (S_e) or perfect (P_e); the tinsmith work can have a riskful (R_i), uneven (U_e) or fine (F) value, the value of supplementary elements can be unreliable (U_r), to be improved (I_m) or in service (I_s); while the chimney shaft value can be unstable (U_s), problematic (P_r) or certified (C_e). The attributes of subgroups and their linguistic categories are represented in Table 1.

B. The Rule Base of the Roof Structure Evaluation

Based on the previously expounded aspects the rule base can be generated as sparse rule base, since the simplification of the calculations on the leaves does not result in significant information loss (this approach reduces the calculation process claims instead). In addition, several observations are not interpretable in some cases, e.g. the "architectural value" of roof framework can be simply omitted.

Based on technical information and experts' knowledge the rules that create the sparse rule base can be easily composed. The different attributes of subgroups as inputs can result in several consequences. Some rules at the roof framework

TABLE II

ATTRIBUTES OF SUBGROUPS AND THEIR CATEGORIES

R_f	roof framework	D_a P_c S_a	dangerous periodic control needed safe
R_c	roof covering	W S_e P_e	weak sensitive perfect
T_w	tinsmith work	R_i U_e F	riskful uneven fine
S_{up}	supplementary elements	U_r I_m I_s	unreliable to be improved in service
C_{hs}	chimney shaft	U_s P_r C_e	unstable problematic certified

(R_f) subgroup represent an example of rule bases:

$if\ P = B_s\ and\ LS_E = S_h\ then\ R_f = D_a;$
$if\ P = S_t\ and\ LS_E = M\ then\ R_f = P_c;$
$if\ P = S_t\ and\ LS_E = L_o\ then\ R_f = S_a;$

On this way 4; 5; 4; 3; 3 rules are composed to the five subgroups respectively that may represent the knowledge about the sub-group evaluation. The Table III. shows the "$if...then$" rules in rows with their consequence at the end sorted by the examined subgroups.

TABLE III

KNOWLEDGE REPRESENTATION IN SUBGROUP ASSESSMENT

P	LS_E	AV	RD	R_f
B_s	S_h			D_a
S_t			D	P_c
S_t	M			P_c
S_t	L_o			S_a

P	LS_E	AV	RD	R_c
B_s			E_a	W
	S_h	L_q	E_a	S_e
		A	R	S_e
S_t	M	A		S_e
E_x		H_q	D	P_e

P	LS_E	AV	RD	T_w
B_s	S_h			R_i
S_t	S_h		E_a	U_e
	M		R	U_e
	L_o		R	F

P	LS_E	AV	RD	S_{up}
B_s			E_a	U_r
S_t	S_h			U_r
S_t	L_o		D	I_s

P	LS_E	AV	RD	C_{hs}
B_s	S_h	L_q		U_s
S_t		A	R	C_e
S_t	M	A		C_e

In the aggregation process, the consequences of the sub-group rules constitute the antecedents in the $if...then$ clause on a higher level. The sparse rule base of the roof structure condition evaluation may be assembled based on experiences and professional knowledge. As a result, the characteristic of the examined roof structure (RS) can be unsuitable (UN_n), acceptable (A_c) or good (G). The dominant sparse rules are arranged in Table IV.

TABLE IV
KNOWLEDGE REPRESENTATION OF ROOF STRUCTURE (RS) ASSESSMENT

R_f	R_c	T_w	S_{up}	C_{hs}	RS
	W	R_i	U_i		UN_s
D_a				U_s	UN_s
P_c	W		I_m		UN_s
P_c	S_e	U_e		P_r	A_c
		F	I_s		A_c
P_c	S_e	F		C_e	G
S_a	P_e		I_s		G

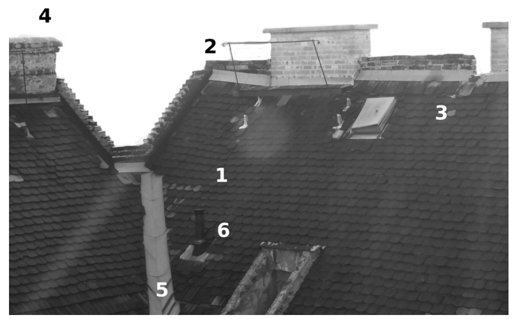

Fig. 5. External appearance of the examined roof structure. Notes: *1*: low load-bearing capacity of tile battens resulted in valley on the roof tiling surface; *2*: unstable catwalk makes the chimney control impossible; *3*: cracked tiles resulted in leaking points; *4*: unstable masonry structure of chimney shaft; *5*: outdated valley flashing resulted in leaking points; *6*: uncertain perforation of supplementary element as a leaking point

C. Condition Evaluation of an Existing Roof Structure

The circumscribed model that combines the Fsig with FRI (as aggregation method) was applied for evaluating an existing roof structure of a classic residential house located in a historic district of Budapest. This house has typical building constructions and failures that characterize well the physical condition of the ordinary historic residential buildings.

The roof consists of wooden framework made with traditional carpenters' technique; a visual examination observed that in several specific locations the tile battens and the main structures (rafters, purlins, trusses, etc.) are injured (cause: moisture).

The roof covering is ceramic tile (mixed types and arrangements). It is clearly visible that the life span of the covering has ended (almost the 90% of the total covering is around eighty years old); and the tiles represent a low quality material and solution.

The flashing (in the valleys, at walls, and around the chimneys) are made with traditional method and of traditional materials. In some areas the fastening disappeared; in other cases the metal fatigue resulted in crackings on its surface.

Some supplementary elements are totally unnecessary (e.g. aerials); they cause leaking problems in roof covering only. The physical condition of catwalk is serious: in its current condition the regular control of chimneys is insolvable.

The masonry structures of chimney shafts are partially renovated, since the legal operation of heating system is allowed in safe chimney structures only. Some chimneys are disused, their physical condition is under the acceptable state.

A typical detail of examined roof structure is represented in Fig. 5.

D. Results

As the first step, the observed conditions of subgroups can be evaluated with FRI method. Based on the technical literature, it is ascertainable that the piecewise linear interpolation can be applied as a good approximation in the given case. After the evaluation process on the sub-group level with the same interpolation method the aggregated result produces the value of roof structure; that may also determine the overall value of the examined building on a higher level. As an example, the initial steps in interpolation of roof framework performance are presented in Fig. 6. The interpolation results on subgroup level are represented in Table V.

TABLE V
INTERPOLATION RESULTS ON SUBGROUP LEVEL

	R_f	R_c	T_w	S_{up}	C_{hs}
$P(\%)$	35%		30%	10%	33%
$LS_e(0-100yrs)$	20	15	30		10
$AV(0-10)$		2			
$RD(0-10)$			4	3	5
Result (subgroup level)	(P_c)	(S_e)	(R_i)	(U_r)	(P_r)

With the support of interpolation method the general condition of the roof structure can be evaluated based on the sparse rule base of the roof structure assessment. The conlusion (C_{RS}) is calculated with the application of fundamental equation of the fuzzy rule interpolation (FERI, [33]). So the final result is $C_{RS} : 1.3 \bigtriangleup 5.3$, where $i \bigtriangleup j$ stands for a symmetrical membership function with support $[i, j]$. This result determines the general condition evaluation of the given building as a child node (RS) on a higher level (C_{TOT}).

As it is mentioned above, the previously applied methods have distinct results to physical condition, service life span, and other aspects. Therefore it is not possible to compare the discussed building condition evaluation to another numerical evaluation methods. The statements of existing building diagnostic surveys are available for comparison. They declare that the quality of the total roof structure corresponds to the condition of an ordinary roof structure with the same age and circumstances, however some important interventions have to be done for preventing serious defects. In the sense of a general evaluation of the building condition the obtained result fits well to this linguistic approach.

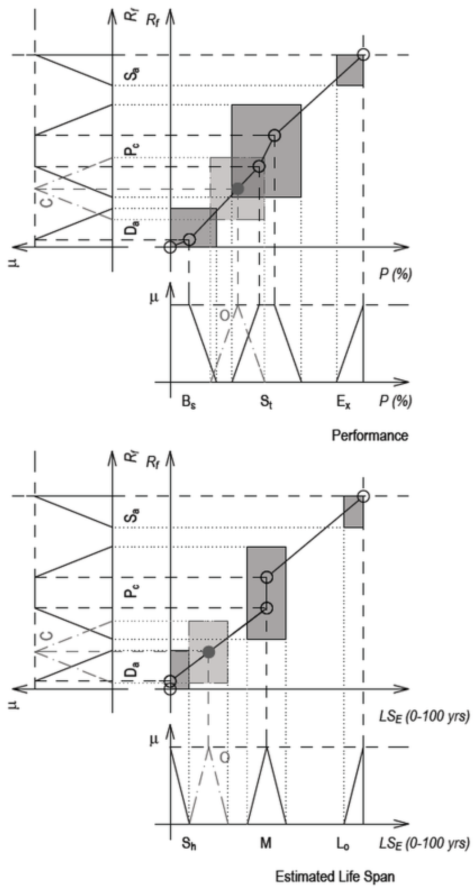

Fig. 6. Piecewise linear interpolation of rules in case of preformance (P) and Estimated Life Span (LS_E) evaluation of the examined roof framework R_f

VI. Conclusions and Future Works

The proposed method conforms well to verbal description of an expert during a diagnostic survey; moreover, a Fsig based evaluation may take several non-measurable factors (as architectural value) into consideration.

The state description of residential building with the introduced method may be a good solution for fast evaluation in case of decision making about the repair method. The complexity of data structure and numerous value factors may resulted in limited but high number in rule base. The application of FRI may reduce these rules to rational and manageable amount.

In this paper the theoretic background and the computing model of the condition evaluation method is discussed. In the future, several analyses may help refining the method and its limitations. As an important question the possibility data loss and misleading results during aggregation process has to be investigated. As an optional extension of this model, the comparison ability of alternative repair solutions may support effectively the renovation phase of old residential houses.

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