Fuzzy Signature State Machine-based Building Refurbishment Chain Optimization

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Abstract: The historic district of Budapest, Hungary that was mainly developed before the Second World War consists of urban-type residential houses. The external view of these buildings indicates that the physical condition of these houses are acceptable, however, a thorough professional examination may contradict to this supposition at the same time. Among others, the absence of any effective decision support tool that helps the owners in determining the refurbishment chain hinders the retrofit of such old residential houses.
This paper represents a new formal method and approach for generating such tool that considers the costs and feasibilities of alternative refurbishment solutions with professional data obtained from building diagnostics surveys and official contractors' billing database.

Keywords: urban-type residential house, building renovation chain, fuzzy signature, fuzzy state machine)

1. Introduction

Among others, the composition of the residential building stock demonstrates well the life quality of the given location. In this respect, the distribution of almost one million apartments in Budapest, Hungary presents a fairly heterogeneous picture: the apartments in urban-type residential buildings (built before the WWII) take 27% [1]. These pre-war urban-type residential houses represent a peculiar set of the apartment building stock; their main characteristics are the decorative street façades, the existence of courtyard and air-shafts; the presence of apartments differentiated by size and orientation in the same building and the traditional masonry and timber load bearing structures.

With a mathematical approach a house can be considered as an ordered composition of specific building components (made of various materials and technology). As a result of a constructional analysis, their hierarchical structure gives a comprehensive picture of the overall house. Following this structure, sets of components exist that can be decomposed into subsets (e.g. the tiling and the tile battens form a subset of roof coverings that is a member of the set of roof structure). A member of a subset or a set can not belong to another subsets or sets.

Due to several causes the average physical condition of these old residential buildings is below standard. The symptoms of overall physical obsolescence (such as uncertain load-bearing performance of inter-floor slab systems and side corridors, outdated mechanical and electrical systems, deteriorated roofing components, etc.) and deterioration (leakings, soakings, etc.) are clearly observable, even in representative urban areas.

At this point it is important to underline that the state transition of a building (as a complex structure of several building components) can be described with a *continuous function*, where the recovery works (or regularly performed maintenance interventions) and deteriorations influence its shape. In extreme situations, the physical condition of the examined building may change, therefore the state transition function may become fractionally continuous.

For designing a tool that may support the owners' decision-making in refurbishment processes, first the possible steps have to be examined, taking their respective importance, interrelations and some non-constructional (e.g. economic, aesthetic, etc.) aspects into consideration. In our approach, the main goal of the tool is to examine each step that is essential for renovating the given building from its present (deteriorated) state to the acceptable (renovated) state.

As a summary of the above statements the followings are ascertainable:

1. The physical condition of any building can be characterized with a continuous state scale.
2. The building is constituted by a hierarchically ordered component structure.
3. The state transition of the building is continuous in time; decay and renovation phases may slightly modify the transition.

2. A Model Proposed for Supporting the Building Refurbishment

In our previous work [2] the theoretical background of the model and attempt for handling the compound technical problem has introduced. The proposed tool that we call *Fuzzy Signature State Machines (FSSM)* is based on the principles of fuzzy signatures with the combination of fuzzy state machines.

The most important reason for applying fuzzy signatures here as the starting point is the fact that the structure of building condition evaluations follows the architectural and civil engineering common sense, where the sub-structures and components of each building are arranged in hierarchical tree-like structures, where the whole building might be presented by the root of the tree and each mayor sub-component is a first level branch, with further sub-branches describing sub-sub-components.

The fuzzy signature structures have a characteristic feature that plays an important role in handling uneven building diagnostics surveys in depth and accuracy of the evaluation: the membership degree reduction may help in operations among fuzzy signatures with partially different structure by finding the largest common sub-structure and reducing all signatures to that level. As an example, maybe in ”survey *A*” the roof structure is considered as a single component of the house and is evaluated by a single linguistic quality label, while in ”survey *B*” this is done in detail and tiles, load-bearing structure, tinsmith work, chimney shafts, etc. are described separately.

Finite State Machines are determined by the sets of input states X, internal states Q, and the transition function f. The latter determines the transition that will occur when a certain input state change triggers state transition. There are several alternative (but mathematically equivalent) models known from the literature. For simplicity the following is assumed as the starting point of our new model:

$$A = \langle X,Q,f \rangle \tag{1}$$

$$f : X \times Q \rightarrow Q, \text{ where } X = \{x_i\} \text{ and } Q = \{q_i\} \tag{2}$$

Thus, a new internal state is determined by the transition function as follows:

$$q_{i+1} = f(x_i,q_i) \tag{3}$$

In matrix form:

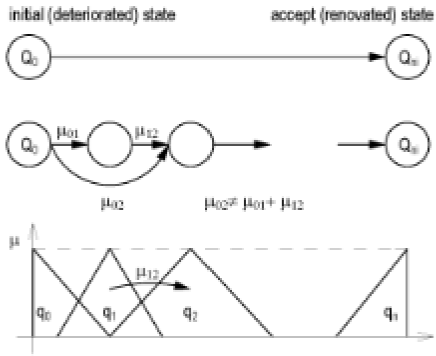

Figure 1. Initial, internal and accept states of a possible renovation process. The bottom diagram represents an internal (μ_{12}) transition between q_1 and q_2 states

$$F = \begin{bmatrix} f(x_1,q_1) & f(x_2,q_1) & \dots & f(x_n,q_1) \\ f(x_1,q_2) & & & f(x_n,q_2) \\ \vdots & & & \vdots \\ f(x_1,q_m) & f_(x_2,q_m) & \dots & f(x_n,q_m) \end{bmatrix} \tag{4}$$

The transition function/matrix maybe interpreted with help of a relation R on $X \times Q \times Q$,where $R(x_i,q_j,q_k) = 1$, if $f(x_i,q_j) = q_k$; and $R(x_i,q_j,q_k) = 0$, if $f(x_i,q_j) \neq q_k$.

The states of the finite state machine are elements of Q. In the present application an extension to fuzzy states is considered in the following sense. Every aspect of the phenomenon to model is represented by a state universe of sub-states Q_i. The states themselves are (fuzzy) subsets of the universe of discourse state sets, so that within Q_i a frame of cognition is determined (its fineness depending on the application context and on the requirements toward the optimisation algorithm), so that typical states like ”Totally intact”, ”Slightly damaged”, ”Medium condition”, etc., up to ”Dangerous for life” are considered. Any transition from one state to the other (improvement of the condition, refurbishment or renovation) involves a certain cost c. In the case of a transition from q_i to q_j it is expressed by a membership value $\mu_{i_j} = c(q_i,q_j)$. In our model the added cost $\Sigma\mu_{i_j}$ along a path $q_{i_1} \to q_{i_2} \to \dots \to q_{i_n}$ is not usually equivalent with the cost of the transition μ_{i_n} along the edge $q_{i_l} \to q_{i_n}$. This is in accordance with the non-additivity property of the fuzzy (possibility) measure and is very convenient in our application, as it is also not additive in the case of serial renovations.

In the case of fuzzy signature machines each of the leaves contains a sub-machine with the above property. The parent leave of a certain sub-graph is constructed from the child leaves, so that the sub-machine

$A^i = A^{i_1} \times A^{i_2} \times \cdots \times A^{i_m}$, and thus the states of A^i are $Q^i = Q^{i_1} \times Q^{i_2} \times \cdots \times Q^{i_n}$, so that the transition $Q^{j_1} \to Q^{j_2}$ in this case means the parallel (or subsequent) transitions $q_{j_{1_1}} \to q_{j_{1_2}} \times q_{j_{2_1}} \to q_{j_{2_2}} \times \cdots \times q_{j_{n_1}} \to q_{j_{n_2}}$. A special aggregation is associated with each leaf; similarly as it is in the fuzzy signatures, however, in this case the aggregation calculates the resulting cost $\mu_{j_{1_2}}$ of the transition $q_{j_1} \to q_{j_2}$, so that $\mu_{j_{1_2}} = c(q_{j_1},q_{j_2}) = a_j(c(q_{j_{1_1}},q_{j_{1_2}}),c(q_{j_{2_1}},q_{j_{2_2}}),\cdots,c(q_{j_{n_1}},q_{j_{n_2}}))$, where a stands for the respective aggregation. (Note that these aggregations sometimes do not satisfy the symmetricity property of the general axiom structure of aggregations, thus it may be referred as a "non-symmetric aggregation".)

It should be mentioned that the selection of aggregation operator is a key issue that may determine the final result of the model; however, the signature structure makes the application of different aggregation methods possible for each node.

With the support of common technical literatures such as [4, 5] the renovation of the urban type pre-war residential houses can be decomposed into eight (more or less) distinct sequences corresponding to the statements in Section 1. With further analyses these sequences may be decomposed into sub-sequences; at the leaves of this tree-like structure are represented by the states of the constructions and building elements. With the application of the existing building diagnostics surveys the initial state of examined building components or groups of components can be determined (note that the fuzzy signature structure obtains solution for handling missing or undiscovered data in the child node level).

3. Conclusions and Future Works

The presented determination of the physical condition and the refurbishment sequences of pre-war residential houses give a general state description and provide the necessary maintenance steps for the mentioned building type only. Another seriously affected building type that has similar difficulties in refurbishment procedure is the residential house that was built in the inter-war era. The experienced defects are quite different, therefore the renovation sequences of Modern Style residential buildings have to be determined separately.

In general case the optimization of a vectorial fuzzy state machine (with theoretically) unbounded number of components is an NP-hard problem. In practice, the optimization of the refurbishment procedure of any sort of residential buildings always has a limited number of sequences; however this number might be rather high. Thus, our intention for the future is to find a proper heuristics at the basic approach to this optimization task, which is able to provide a quasi-optimal solution for every concrete problem, or a very lightly optimal solution for every problem in a manageable time. These methods seem to be various population-based evolution algorithms, which may be combined with local search cycles (evolutionary memetics), e.g. bacterial or particle swarm algorithms.

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