DEVELOPING AN INTEGRATED DECISION MAKING SYSTEM FOR THE ASSESSMENT OF CLEANING INTERVENTIONS ON MARBLE ARCHITECTURAL SURFACES

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Abstract

In this work, the development of an integrated decision-making system for the assessment of cleaning interventions on marble architectural surfaces is presented. The suggested system resulted by the incorporation of a fuzzy logic model into GIS and its architecture includes: (a) a GIS based graphical user interface for features and attributes retrieval, management comparison, analysis and correlation; displaying the application site of the historic building under investigation, where decay diagnosis and pilot cleaning interventions took place; (b) a database, that contains all the required attribute data sets for the operation of the decision-making system, that is the recorded physical-chemical characteristics of marble surfaces, during different time periods (before and after cleaning); (c) a fuzzy logic model (Mamdani type) as solver, using for input variables cleaning assessment criteria, whereas output parameter is the cleaning performance index. This platform enables the constant response in relation to the cleaning performance under predefined assessment parameters and acceptance threshold levels in a pointed spatial entity and environmental conditions; developing an integrated decision-making system for the assessment of cleaning interventions. The suggested system is demonstrated in practice on marble surfaces of a historic building in Athens, Greece.

Keywords: cleaning, marble, modeling, decision making, fuzzy logic, GIS, cultural heritage

1. Introduction

Cleaning is the par excellence non-reversible conservation intervention, and therefore the compatibility concept that should governs it, relies on the setting of a range of assessment criteria along with the determination of their acceptance threshold levels. In parallel, the decay that the applied cleaning interventions are appointed to remove, depends on the correlation of endogenous and exogenous parameters. Endogenous parameters focus on material physical-chemical characteristics, whereas exogenous parameters depend on surface location and orientation on building scale, protection degree from rain-wash and wind, as well as environmental conditions. Thus, the need

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for taking into consideration all the above-mentioned factors whenever cleaning interventions are to be assessed is high.

In the course of evolving a methodology for cleaning assessment on marble surfaces a fuzzy classification system was developed and successfully used (Delegou and Moropoulou 2008; Moropoulou *et al.* 2008). In this system, cleaning assessment criteria with corresponding parameters and their acceptance threshold levels were defined, based on the recording of the physical-chemical characteristics of the examined surfaces.

However, exogenous parameters were not included in the previous attempt, and therefore a tool to interrelate data between space (building, environment) and endogenous parameters (physical-chemical characteristics of the under investigation building material-surface), taking into account their variation over time, needs still to be addressed.

Within the framework of building pathology representation and building preservation, several scientific projects have investigated GIS potential (Salonia and Negri 2002; Inkpen *et al.* 2001; Moropoulou *et al.* 2005), due to its capabilities of recording, grouping, managing and analysing large volumes of spatially referenced data, as well as for the elaboration of data-bases and spatial data transformation and spatial analysis.

Therefore, the tool for correlating exogenous and endogenous parameters whenever cleaning interventions are to be assessed can be a GIS platform which can enable control and monitoring of the building surfaces under examination, through the processing of different background data like spatial and attribute data sets.

So, in this work an integrated decision-making system for the assessment of cleaning interventions on marble architectural surfaces is presented. The suggested system resulted by the incorporation of a fuzzy logic model into GIS thematic maps elaborated on focused working-scale, according to decay patterns and applied pilot cleaning interventions. The decision making system is demonstrated in practice on the scale of the representative investigation area of a capital of the National Archaeological Museum (NAM) historic building (Figure 1) in Athens, Greece, which presented the characteristic decay of black crust.

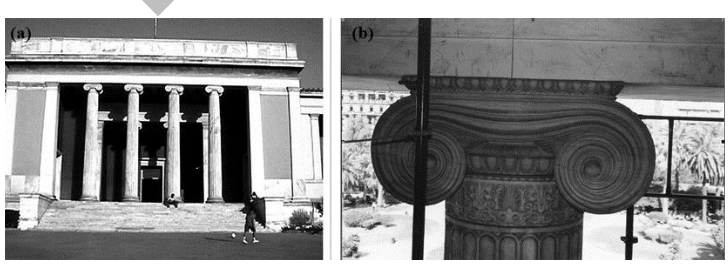

Figure 1. (a) The Historic building of National Archaeological Museum and (b) the representative investigation area of the capital

2. Methods

The following experimental techniques were used for decay diagnosis and the determination of the critical parameters of the cleaning assessment criteria:

Scanning Electron Microscopy with Energy Dispersion by X-ray Analysis (SEM-EDS) is applied on collected monument samples, before and after cleaning, using JEOL JSM-5600, OXFORD LINKTM ISISTM 300 with Energy Dispersive X-ray Microanalysis system, Accelerating Voltage 20 KV, Beam current: 0.5nA, Livetime: 50 sec, Beam diameter <2μm.

Digital Image Processing (DIP) of SEM images using the EDGE program which was developed by the US Geological Survey (Mossoti and Eldeeb 2000; Mossoti *et al.* 2002). EDGE program was developed for the analysis of back-scattered electron-micrograph images consisting of 512 rows with 512 pixels per row, where each pixel is encoded with 8 bits on a 256-shade gray-scale palette. The fractal dimension of the exposed surfaces of stone specimens cut in cross-section is measured, along with the near-surface fracture density (FD) of the stone which is a measure of the fraction of the stone volume filled by fractures, crevices, and pore space (Mossoti and Eldeeb 2000; Mossoti *et al.* 2002). The FD results are reported as the percentage of pixels identified as components of the fractures calculated until 100μm under the surface area.

Laser Profilometry (LP): 3-D micro-topography plots of the monument collected core samples were attained using the Proscan 2000 with a laser triangulation sensor of 1μm resolution. The roughness parameter Rq was estimated, according to BS EN ISO 4288:1988, whereas the ratio of actual to projected surface area was measured at each micro-topography.

Colorimetry: The Dr Lange color-pen LMG159/160 colorimeter, was applied in situ on the investigated marble surfaces, for measuring the L*, a*, b*, according to CIELab Uniform Color Space. Total color difference ΔE, was estimated according the ASTM D2244-93.

Moreover, the GIS thematic maps were elaborated in ArcMap/ArcInfo 9.2, using the CAD architectural drawings as the blueprint for the GIS base-map development.

Finally, a Mamdani type of fuzzy model (Mamdani 1974) was developed under Visual Studio using the C^{++} programming. Information flow through a fuzzy model requires that the input variables go through three major transformations before exiting the system as output information, which are known as fuzzification, fuzzy inference, and defuzzification (Vakalis *et al.* 2004; Moropoulou *et al.* 2008). The three steps are depicted in Figure 2, which shows the structure of a fuzzy logic model.

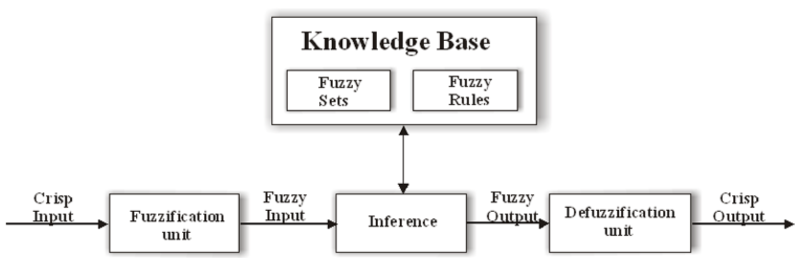

Figure 2. The structure of a typical fuzzy logic model

3. Results & Discussion

3.1 Architecture of the decision making system

The architecture of the suggested decision making system, as well as the information flow within the system are presented in the diagram of Figure 3.

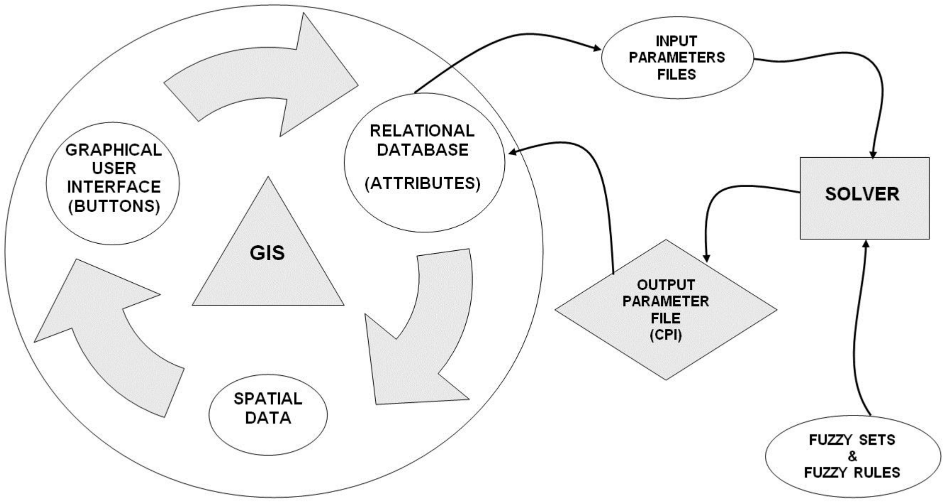

Figure 3. Architecture of the integrated decision making system for the assessment of cleaning performance

Two are the main parts of the suggested decision making system. The first one includes the GIS based graphical user interface for features and attributes retrieval, management, comparison, analysis and correlation. Spatial classification of decay and pilot cleaning interventions on the representative investigation areas, is taking place through the building of the thematic maps of decay and pilot cleaning interventions, respectively. Moreover, attribute databases consisting of physical-chemical characteristics' data are elaborated and linked to the attribute table of the corresponding GIS decay/pilot cleaning interventions' mapping project, thus resulting in relational databases (RDBs).

Finally, the thematic map of "conservation interventions' planning" is the resulting output theme of both decay and pilot cleaning interventions' thematic maps, after the application of the geo-processing analysis of the intersection operational tool. This new thematic map includes spatial information and attributes before and after cleaning; accomplishing comparison and analysis of the recorded to space physical-chemical characteristics of marble surfaces, during different time periods (Delegou *et al.* 2011).

The second main part of the suggested decision making system is the solver of the fuzzy logic model. The critical parameters of the cleaning assessment criteria are used as input parameters of the model, comprising in parallel data entries in the RDB of the thematic map of pilot cleaning interventions. As it is summarized in Figure 4, the input variables of the fuzzy model are (Moropoulou et al. 2008): (a) Patina preservation index-PPI (%), (SEM-EDS results); (b) Preservation index of gypsum layer-PIGy (%), (SEM-EDS results); (c) Fracture density, FD (%), (DIP of SEM images results); (d) Actual/Projected area ratio, r, (LP results); (e) Roughness (μm), (measured parameter: Rq; LP results); (f) Total color difference, ΔE, (Colorimetry results). In both cases of the input parameters of "patina preservation index" and "preservation index of gypsum layer", input values are expressed in percentages, in order to have comparable input data for the fuzzy model from different surfaces of black crusts.

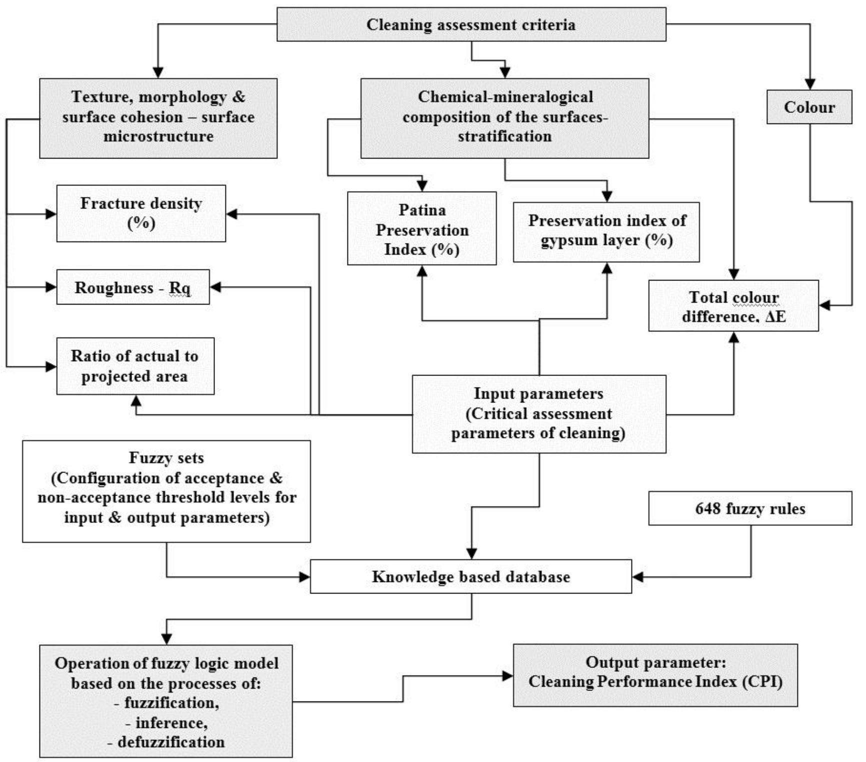

Figure 4. Flow chart presenting the development of the fuzzy logic model for the assessment of cleaning performance on black-grey crusts surfaces

Table 1. Definition of fuzzy sets for all input and output parameters of the fuzzy model

Input parameters– Output parameter	**Definition of fuzzy sets**			
Patina preservation index (%)	Low (0-70%)		High (50-100%), accepted	
Preservation index of gypsum layer (%) (PPI)	Low (0-40%)	Medium (30-70%)	High (50-100%), accepted	-
Fracture density (%) (FD)	Low (0-10%)	Medium (8-25%), accepted	High (18-35%)	Extra High (30-60%)
Ratio of actual to projected area (r)	Low (1-1.5)	Medium (1.25-3), accepted	High (2.5-4)	-
Roughness Rq (μm)	Low (0-10 μm)	Medium (5-20 μm), accepted	High (15-50 μm)	-

Total colour difference (ΔE)	Low (0-6)	Medium (5-15), accepted	High (13-40)	-
Output parameter: CPI	Non-accepted (0-4.5)	Medium (4-7.5)	Accepted (7-10)	Optimum-recommended (8-10)

In particular, quantitative and qualitative observations deriving from SEM-EDS regarding width, cohesion, continuity and homogeneity of patina/gypsum layer, are expressed in percentage in comparison to the corresponding data before cleaning applications. Therefore, variances of the examined layers in width and cohesion, from different areas or buildings can be classified in the designed fuzzy model.

During the development of the fuzzy sets the acceptance and non-acceptance threshold levels are configured for all input and output parameters, as shown in Table 1. Cleaning Performance Index (CPI) is defined as the output parameter, which classifies the cleaning interventions into non-accepted, medium, accepted and optimum-recommended ones.

Additionally, 648 "IF-THEN" fuzzy rules are developed using the logical operation "AND" (Moropoulou et al. 2008). Fuzzy rules development was based on the knowledge and experience that was acquired by the lab and in-field experimental results of 34 different and real scenarios of cleaned black crusted marble surfaces, taking under consideration the international bibliography of cleaning assessment thematic area, since an outcome should be given (output parameter–CPI) to each possible combination of each input parameter set. The operation of the fuzzy logic model was based on the processes of fuzzification, inference, and defuzzification.

It is worth-mentioning though that data movement within the system is accomplished by 2 intermediate files; the first extracts data from the RDB and the second loads and stores data into the RDB, after the code execution (Figure 3). In particular, the values of the critical cleaning assessment parameters (for every pilot cleaning intervention) are extracted from the corresponding fields of the RDB of the cleaning interventions' thematic map to an intermediate file. This intermediate file feeds the solver (that is the fuzzy logic model) with the values of critical cleaning assessment parameters which are its input parameters. In succession, the executable code is retrieved, along with the fuzzy sets and the fuzzy rules whereas the results of the output variable (CPI) for every examined cleaning are stored into a new intermediate file. Data of this second intermediate file are retrieved by GIS and the CPI values are stored in the RDB of the thematic map of the conservation interventions' planning. All the above mentioned operations are achieved by the user when the GIS graphical interface is employed along with the activation of two extra buttons specially created for the generation of the two intermediate files.

In addition, cartographic attribution of CPI sets into the spatial entities of the thematic map of conservation interventions' planning can take place using the GIS capabilities. CPI is classified according to the threshold levels of the output parameter of the fuzzy logic model expressed though as crisp sets. Whenever CPI value changes set (because new data entries are imported into the RDB) the colour of the corresponding spatial entity (that is a cleaning intervention) automatically changes, indicating the new set under which the cleaning is classified.

3.2 Demonstration in practice: The case study of the historic building of National Archaeological Museum in Athens

Within the context of the above methodological approach, three representative marble surfaces of the NAM were selected to act as pilot projects for cleaning assessment, one of which is hereby presented. In neoclassical buildings like NAM, marble is used as facings or load-bearing structures, presenting smooth or relief finishes. The representative marble surface of the capital was selected due to its high artistic value as a sculptured surface and the arising challenges on conservation issues for the preservation of relief surfaces. The capital under investigation is located on the first (from North) column of the propylon, has an eastern orientation, and is totally protected from rain-wash.

Decay and pilot cleaning data comprised the attribute data sets which describe the characteristics of the recorded spatial entities of the investigated surface. Therefore, ascribing the decay and cleaning results of the physical-chemical study to the features of the GIS base map, during building topology, led to the development of the thematic maps of decay and pilot cleaning interventions (Figure 5).

In decay thematic mapping each layer was classified and recorded according to its spatial properties and physical-chemical characteristics, before cleaning treatments. The sculptured surface of anthemia present front and side relief surfaces for which decay diagnosis results had indicated different physical-chemical characteristics like patina layer width and cohesion, gypsum layer width, roughness, surface area and fracture density. Therefore, two different layers were elaborated, one for each relief surface (front and side), which were displayed by light and dark grey respectively, along with 2 representative SEM images in Figure 5, left.

Furthermore, accordingly to the decay thematic map, two different layers were elaborated in the pilot cleaning interventions thematic map, one for each relief surface (front and side), whereas the areas of the pilot applications of the different cleaning methods were elaborated as features and displayed by different colours (Figure 5 right).

Moreover, attribute databases consisting of physical-chemical characteristics data were elaborated and linked to the attribute table of the corresponding GIS decay/pilot cleaning interventions' mapping project, resulting in relational databases (RDBs). In particular, the GIS attribute tables, which include topological characteristics like perimeter, area and adjacency info were linked with external databases, where data regarding petrography, chemical and mineralogical composition and stratification, total crust width, patina occurrence, macro-crystalline gypsum layer width, and micro-crystalline gypsum layer width (results of SEM-EDS); roughness Rq and Actual/Projected area ratio (LP results); fracture density (DIP of SEM images results); luminosity L, difference in red-green a*, difference in blue-yellow b*, and total colour difference ΔE (colorimetry results in CIELab colour space) were stored and classified. The databases were built using text and numerical elements as type of entries; whereas the data fragmentation permits the user to interrelate data regarding decay diagnosis and pilot cleaning interventions with the vector data, locating the info in a geometrically exact point or area, respecting the topological relationships among the various parts of the investigated surface. It is obvious that in the case of the RDB of the pilot cleaning thematic map the data of the critical cleaning assessment parameters are included as they comprise the input variables of the fuzzy model.

Using geoprocessing procedure and in particular the intersection operation tool for both decay and pilot cleaning interventions thematic maps, the resulting output theme is the conservation planning thematic map presented in Figure 6. This output theme contains combined spatial information and the aggregation of the attribute data of both decay and pilot cleaning intervention thematic maps.

Data movement across the integrated decision making system was accomplished by using the two extra buttons presented in Figure 7, specially created for the generation of 2 intermediate files. The activation of the first button extracts the values of the critical cleaning assessment parameters from the RDB of the pilot cleaning thematic map. The activation of the second button loads and stores the values of CPI into the RDB of the conservation planning thematic map, after the code execution. Some representative results from the test run of the fuzzy model are presented in Table 2.

CPI was classified according to the threshold levels of the output parameter of the fuzzy logic model expressed though as crisp sets, and displayed by different colours, as it is demonstrated in Table 3, and in Figure 8, left. When new data regarding the critical cleaning assessment parameters (which actually are the input parameters of the fuzzy logic model), give for the finally selected and applied cleaning intervention, values of $4.5<CPI<7$ (set of medium cleaning, mainly expressing the under-cleaning), then periodical conservation interventions on the marble surfaces of the investigated decay of black crust could be scheduled (Figure 8, right).

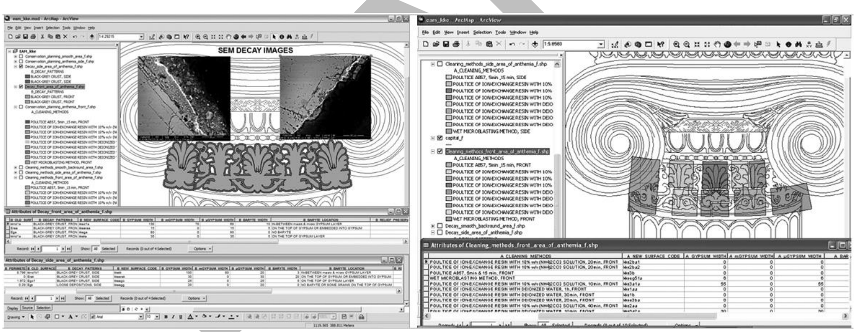

Figure 5. Thematic map of decay for the capital surface with corresponding RDBs and SEM decay images for both front and side anthemia surfaces (left). Thematic map of pilot cleaning interventions for the capital surface with the RDB of the front anthemia surface (right)

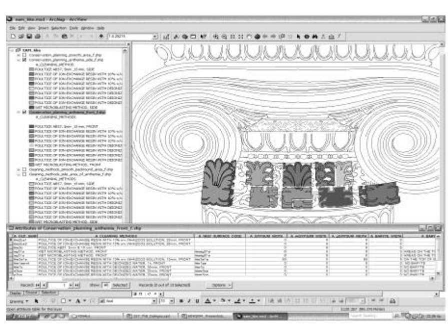

Figure 6. Thematic map of conservation interventions' planning for the capital surface with corresponding RDB

Figure 7. The two extra buttons specially created for the generation of the two intermediate files which permit data movement within the system

Table 2. Representative results of the fuzzy model. Values of crisp inputs (results of experimental techniques- critical assessment parameters of cleaning) – Values of output (CPI)

Pilot Cleaning Interventions	**Values of Crisp Inputs-Results of experimental techniques**						**Output**
	PPI (%)	**PIGy (%)**	**FD (%)**	**r**	**Rq (μm)**	**ΔE**	**CPI**
DS&NC[1] (10min)	90	90	16.10	1.914	17	7.21	8.14
DS[2] (10min)	25	80	23.10	1.542	11	9.56	6.62
AB57[3] (5&15min)	1	1	11.20	1.740	10	15.30	3.36
Wet micro-blasting Method[4]	65	70	36.60	2.593	30	6.48	6.65

[1]: Poultice of ion-exchange resin with 10% w/v $(NH_4)_2CO_3$ solution; [2]: Poultice of ion-exchange resin with deionized water; [3]: Poultice AB57 (1lt deionized water, 30gr NH_4HCO_3, 50 gr $NaHCO_3$, 25 gr of bi-sodium EDTA, 10ml Desogen, 800gr sepiolite); [4]: Wet micro-blasting method where spherical particles of calcium carbonate (diameter <80μm), were springing with a maximum function pressure of 0.5bar The proportion of water and spherical particles of calcium carbonate in the device's commixture barrel was 3:1.

Table 3. Classification of CPI

Colour	**CPI Set**	**Description**
Black	0<CPI<4.5	Non-accepted cleaning
Dark grey	4.5<CPI<7	Medium cleaning
Light grey	7<CPI<8	Accepted cleaning
Cross hatched	8<CPI<10	Optimum-recommended cleaning

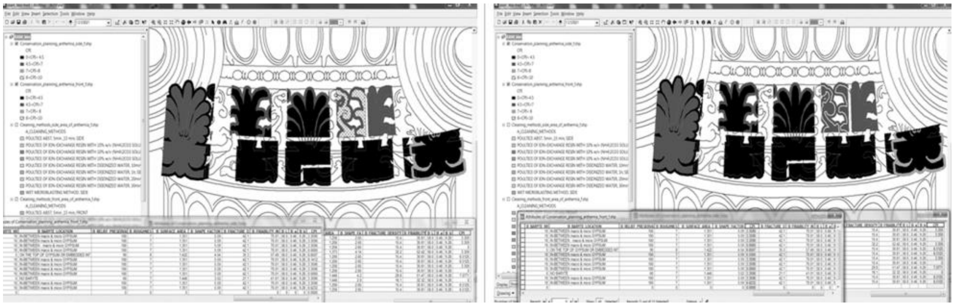

Figure 8. Cartographic attribution of CPI sets into the spatial entities of the thematic map of conservation interventions' planning (left). Spatial entity of the cleaning intervention of ion exchange resin with $(NH_4)_2CO_3$ applied for 10 min, when CPI value changes from 8.14 (cross-hatched area in this Figure left) to 6.5 (dark grey area in this Figure right).

4. Conclusions

The development of an integrated decision making system for the assessment of cleaning interventions, with ultimate goal the scheduling of the periodical conservation interventions, is presented. This system resulted by the incorporation of a fuzzy logic model into GIS, and it was successfully demonstrated in practice for the assessment of pilot cleaning interventions applied on black crusted marble surfaces. This platform enables the constant response in relation to the cleaning performance under predefined assessment parameters and acceptance threshold levels in a pointed spatial entity and environmental conditions.

5. Acknowledgements

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