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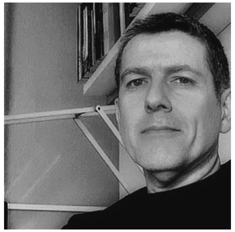

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Segmentation protocols in the digital twins of monumental heritage: a methodological development

The paper shows an advancement of the research that the authors have been carrying out in recent years in semantic structuring of digital architectural representations field, with a focus on the issue of uncertainty of annotations.
The studies carried out in this regard have shown how the domain experts specialization determines a vision and interpretation of the same architectural object that we could define “categorized”. The interest was, then, in verifying which categories of experts have a greater degree of agreement in classifying and segmenting architectural elements, to highlight which specializations contribute the most in enriching the semantic reasoning about such forms.
Aiming to broaden this reasoning, the research was deepened with annotation sessions concerning architecture examples that didn’t correspond to the classical orders rule but included wider fields of historical heritage (from sacred to fortified architecture). The aim is to verify whether the uncertainty of annotation is actually ascribable to a specific segment of the historical heritage, for example: the classical world, or whether the question is broader and as such in needs deeper thinking.

Keywords:
Semantic annotation; uncertainty of segmentation; 3D cultural heritage segmentation; 3D point cloud classification

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1. INTRODUCTION

The paper shows an advancement of the research that the authors have been carrying out in recent years in semantic structuring of digital architectural representations field, with a focus on the issue of uncertainty of annotations.
Recent studies and projects prove a significant evolution in the encoding of semantic segmentation protocols of three-dimensional multiscale models, even adopting machine/deep learning approaches (Grilli et al., 2018; Malinverni et al., 2019; Özdemir et al., 2019) for the identification of meaningful forms.
In general, the organization of shapes around significant concepts is carried forward starting from the manipulation of discrete models gathering from image-based and/or range-based survey activities. On them are identified the most iteratively simple geometric elements that define them, recognized at the cognitive level in accordance with the words of specific domain dictionaries and framed within a system of part-all relationships (fig. 1). The spatial definition of each basic component is carried forward in several ways.
As part of the BIM approach, the modeling of these components focuses on the manipulation of parametric elements, selected within objects families, framed in a system of an architectural representation structuring understood as a collection of semantic entities that are already categorized (di Luggo & Scandurra, 2016; Bagnolo et al., 2019). At the same time, a growing number of studies are interested in the application of semi-automatic algorithms for the decomposition into semantically coherent geometric units carried forward according to the supervised/unsupervised/interactive approach. In this case the semantic classification deriving from the ML/DL algorithms is based on the extraction of essentially geometric features such as covariance, distance from plane, elevation, verticality (Grilli & Remondino, 2019; Matrone et al., 2020). There are also hybrid approaches which, starting from the consideration that it is easier to identify architectural elements on 2D supports rather than 3D models, allow to carry out the segmentation operation in an ambivalent way, exploiting the projective relationships between the two types of supports. This is, for example, the principle underlying the Aïoli collaborative platform developed by the MAP laboratory of the CNRS in Marseille (Manuel at al., 2016; Croce et al., 2020).
However, decomposition into elements attributable to specific semantic concepts is typically carried out within a rigid concept and/or system of topological interactions between solid instances.

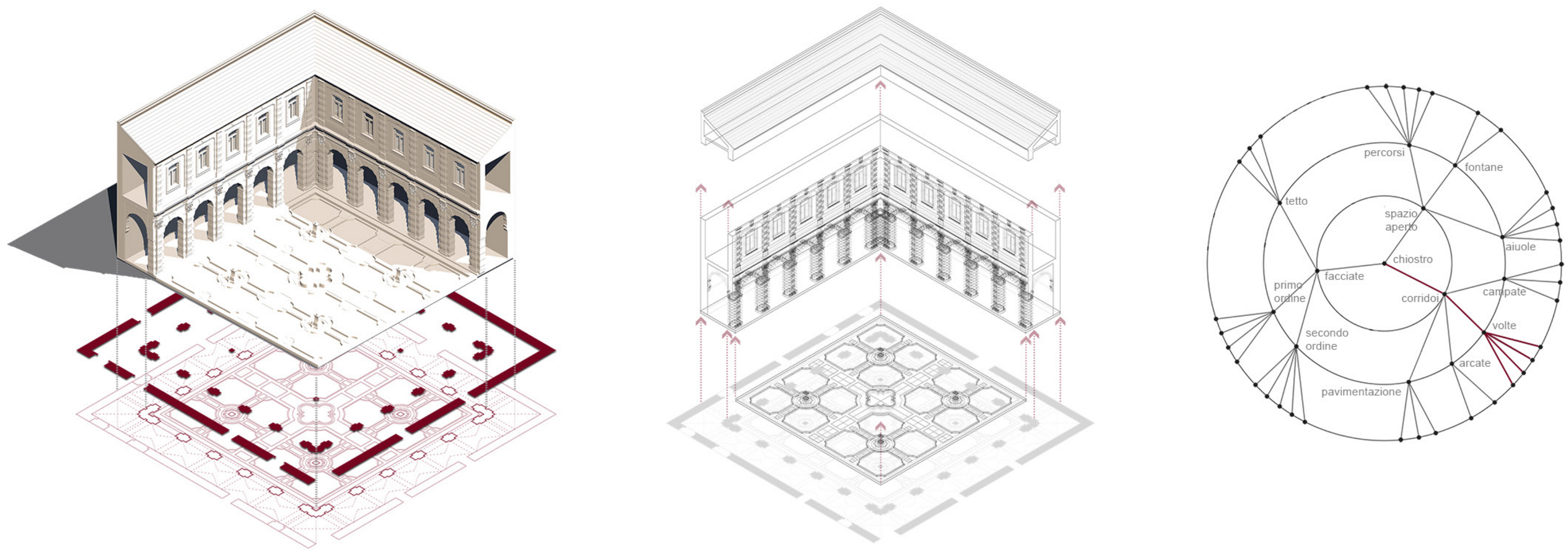

Fig. 1 - Architecture of the XVIII century, arch. Sanfelice. Example of one of the topological-semantic segmentation criteria

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This is hardly suited to historical heritage modelling. In this field, the recognition of semantic forms follows rules and parameters that cannot be provided a priori in an exclusive way because they are extremely linked to the heritage specificity (Campi & Cera, 2019). Indeed, even segmentation protocols using ML that aim to objectify and speed up the operation, when applied to the historical context are not completely generalizable due to the lack of adequate data for training (Teruggi et al., 2020). (M.C.)

2. BASIC ISSUES

The characteristics of the historicized built heritage contribute to make the semantic annotation process extremely uncertain. Given that 'semantic annotation' means the precise identification of the boundary that identifies a specific spatial entity to which an abstract concept recognized within a formalized domain knowledge is connected, this operation is uncertain where the annotator shows difficulty in defining in a unambiguous way a significant architectural element. This happens because the definition of the form to be classified is not limited to the geometric reconstruction, but also cultural, morphological, constructive, structural, material and graphic visualization aspects contribute to its linguistic and semantic recognition.
As mentioned above, the richness of the historical fabric and the heterogeneity of its constituent elements explain the uncertainty of the semantic description. A domain expert has difficulty in giving a unambiguous classification to an object which, often in construction practice and in the evolution of trends, is not immediately ascribable, for example to the theories of classical language.
The observation of real objects shows - for example in the case of the History and Analysis of Architecture and Settlements Library of the Polytechnic of Turin - that for building a column attributable to the Tuscan order, the annulet usually described in the vocabulary of the architect as the last element of the capital, is part, in the real case study, of the shaft, probably due to construction problems. The uncertainty of confinement is therefore obvious and lies in the ambiguity between the architect's vocabulary and the physical divisions of the elements of built architecture.
The support on which it occurs also contributes to making the annotation uncertain. The different modalities of representation and visualization of the same element provide more or less information, in relation to the type of analysis to be carried forward (De Luca, 2006). The choice, for example, of a 3D representation consisting of polygons is particularly effective if the aim is to express the volume of the architectural element, extracting information on the spatial extension in the third dimension. An operation that, on the contrary, is not possible if the support is two-dimensional such as a single photograph, an orthophoto or a technical drawing. However, two-dimensional materials have the advantage of being more easily usable even by annotators who are not familiar with three-dimensional representations and their manipulation. The photorealistic rendering of the buildings, then, produced through the projection on the polygonal model of images as textures, can provide, instead, a useful support for the interpretation and evaluation of the state of conservation of the building materials, enriching the data thanks to the reproduction of the visual appearance of surfaces. It follows that semantic decomposition systems that arrange information around a single representation limit the study that certainly cannot be limited to a single two-dimensional support or to a single three-dimensional representation.
The difficulty of annotation lies, at the same time, also in the influence of the different annotators' background in their critical interpretation of forms and concepts, which is not limited to the simple identification of geometric features. The different specialization of the experts in fact influences their vision and interpretation of an architectural object for which a historian will tend to recognize and isolate architectural components according to different reasons from a designer. The coexistence of diversified arguments makes the semantic description of an architectural form more complex, enriching it with attributes that complete only the geometric genesis. These arguments are evident when they guide the point of view with which the significant elements to be identified in an architectural system are investigated. A structural engineer interested in examining the structural behavior makes an attribution of meaning and confinement of the parts strictly functional to the investigation, grouping and isolating elements of the architecture according to their contribution and response to the stresses due to the supposed forces distribution. In addition, this operation generally develops in a different way based on the type of structural analysis to be carried forward. For example, to study the structural behavior of a masonry building it may be necessary to identify and analyze some collapse mechanisms for which the architectural complex will be discretized into peculiar elements, organized into subsystems according to behavioral logics and with specific geometric, topological and semantic attributes for each mechanism. Moreover, for different identified collapse mechanisms, the same element could assume completely different roles, and therefore be modeled in a different way, or it could even be not identified as it is not directly involved in the specific mechanism.
It follows that the semantic description of architectural forms is guided by logics that are neither general nor generalizable as they are extremely accurate and technical. For example, considerations related to the decorative party, typological and formal characteristics or other discriminating and selective criteria of the various professionals involved in the process of analysis and knowledge of architecture are excluded. (V.C.)

3. THE UNCERTAINTY OF ANNOTATION: FROM PROBLEM TO RESOURCE. CODING OF A REGISTRATION METHOD

The gained observations led the authors to address already in Cera (2019b) the issue of the uncertainty of historical architectures representations annotation made by domain experts conceived as the uncertainty of technicians in indicating exactly the physical boundary in

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which one element ends and another one begins. Specifically, the topic led to the codification of a labelling method taking into account the annotators' differences, of recording them and converting them into information.
The starting point for the methodological theorization was the choice of the way to isolate and associate the parts of the architectural form, morphologically broken down into elements and sub-elements, to the concepts of the chosen vocabulary [1]. The support on which the semantic structuring of spatial data takes place is the digital model itself, in the form of a polygonal mesh since it allows to discern the topology of the individual architectural components easily.
In general, the profit of using a three-dimensional support compared to photographs (without a doubt widely used for labelling by archaeologists and restorers) can be found in the possibility of extracting information related to the attributes in the third dimension of architectural elements, directly manipulating and querying a single complex model instead of a consistent number of single images showing punctual shooting points. Among the three-dimensional representations, then, the benefit of working on a polygonal mesh in place of the point cloud lies in the better understanding of the topology of the individual parts. In a discrete model made of points is often very complex to exactly understand which group of points sets the limit of an object (for example the frame of a window), which point is offset from the others, implying a misalignment / offset of planes. The polygonal model, quite the opposite, simplify the identification of the most basic elements thanks to some expedients for visualizing the model. The Computer Vision thanks to the possibility of querying normals, colors and ambient occlusion maps makes the morphological articulation of an artifact visually clearer.
So, the benefit of working with a mesh support in comparison to the parametric objects produced with the BIM approach is linked to time and necessity. Modeling smart objects, hinged in families regulated by parameters, is a time-consuming operation, especially if the reference architecture stands out from the historical heritage. In addition, BIM modeling is not always essential and necessary. Suffice to know that the projects of museums and digital archives for which it doesn't necessarily mean that such complex and articulated models are indispensable, so that not all the investigation and intervention objectives require a representation of the data ordered according to the logic of BIM.

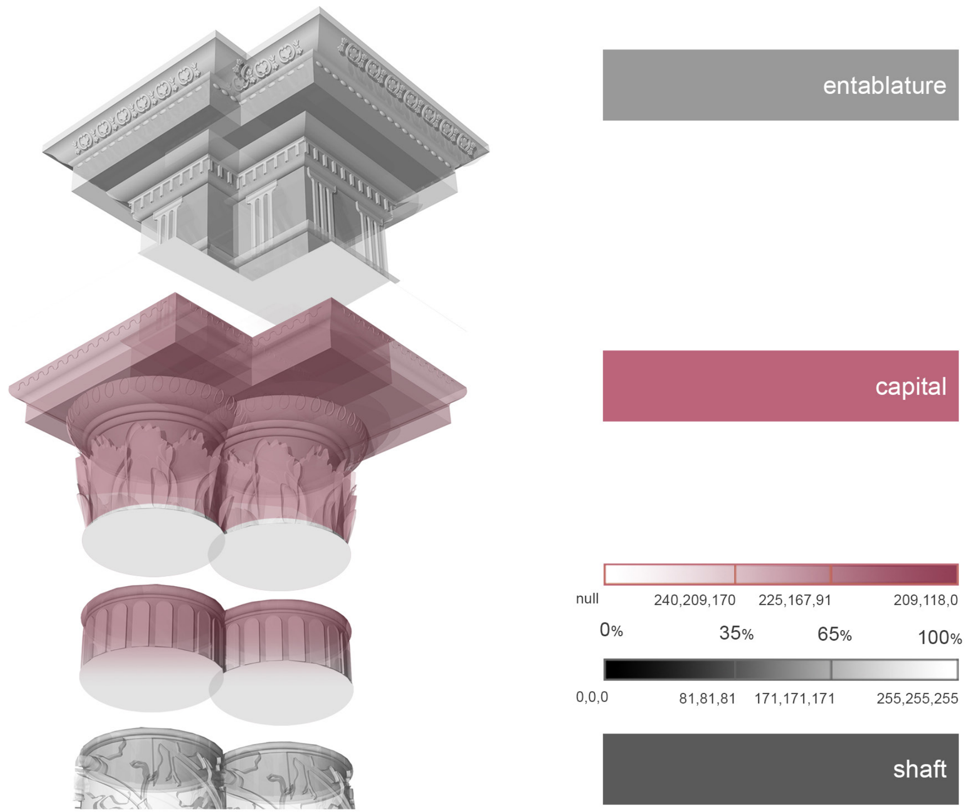

Fig. 2 - Use of the gradient by an annotator. Example for the annulet concept

Starting from the polygonal model, the theorized segmentation is carried out by highlighting by a color, for the semantic concept "x", the relevant polygons of the architectural artefact through an action of "painting". The coloring intended as selection and therefore identification of the polygons can be carried out both directly on the model and on its development on the image plane since the tool used is a

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professional texturing software [2] which exploits the geometric correspondence between three-dimensional elements and UV space. The two representations are therefore connected to each other so that the highlighting made on one is automatically transferred to the other.
The operation just described produces as an output a map that is called 'semantic map'.
It is a monochromatic image which, by virtue of the aforementioned 2D/3D geometric correspondence, specifies which portions of the overall object are relevant to a given semantic concept and its degree of relevance. Specifically, the color indications used are recorded in binary code where white specify high relevance, while black specify no relevance. Therefore, the map records in a purely visual code which polygons, in the digital model, are relevant to the represented concept, using the UV map of the model.
The information is made recoverable and searchable since the map is linked with the digital architectural model as a texture, i.e. the transfer of the information contained in the semantic map of the digital model exploits, in an inverse way, the 2D/3D correspondence as it already happens in three-dimensional modeling, when the vertices of the mesh are related to the pixels of the color map, in order to produce a coloured model.
As a result, this system introduces an improvement in comparison to the approaches already codified since, first of all, it does not require the "physical" decomposition of the discrete model (which would entail obvious wastes in terms of analysis and running times); moreover, being based on the existing correspondence between the three-dimensional space and the 2D plane, the proposed labeling system allows the migration of annotations between different representations of the model, of which it exploits and considers only the spatial coordinates for the association of semantic descriptors (Cera, 2018a).
If the assumption from which the research was born is the awareness of the confinement uncertainty in the annotation process by domain experts, it follows that the coded protocol structures the tools to allow annotators to refine the quality of semantic data. In detail, the possibility of using gradients is provided, thus allowing to express not only a binary relevance of each vertex for a given concept but also a level of relevance for it. This occasion is important in the field of architectural heritage as it is not always possible to classify an element unambiguously or indicate exactly where it ends up becoming another; and becomes useful when it cannot be assigned to a specific category.
An example is the one underlined in the previous paragraph for the university library of Turin. In this case, as in many others that affect the historical fabric, working in a traditional way, the segmentation of the model should be diversified according to the type of analysis to be carried forward. However, this analysis does not include the assessment of the relevance and/or pertinence of an element in relation to a specific concept or rather the molding in question, how relevant is for the concept of capital (according to the formal analysis) and how much it is for the concept of shaft (from a structural and material point of view).
The semantic mapping with gradients system allows to overcome and solve this complexity.
The annotator uncertainty is then recorded on the map in the form of a grayscale, giving all users the opportunity to express their evaluations and any doubts about the perimeter and relative classification of a geometric component. The annotator will be able to highlight in white the polygons of the model that for him respond to the concept of the pillar, for example, using a 100% while; using shades of gray he can underline an increasingly lower percentage of relevance up to black, that is the colour attributed to polygons that are not linked with the reference concept (fig. 2).
Given the basic reasons set out at the beginning, the research was examined in depth since the annotation method cannot be considered exhaustive if carried out by a single domain expert. In fact, several professionals are involved in the process of knowledge, documentation

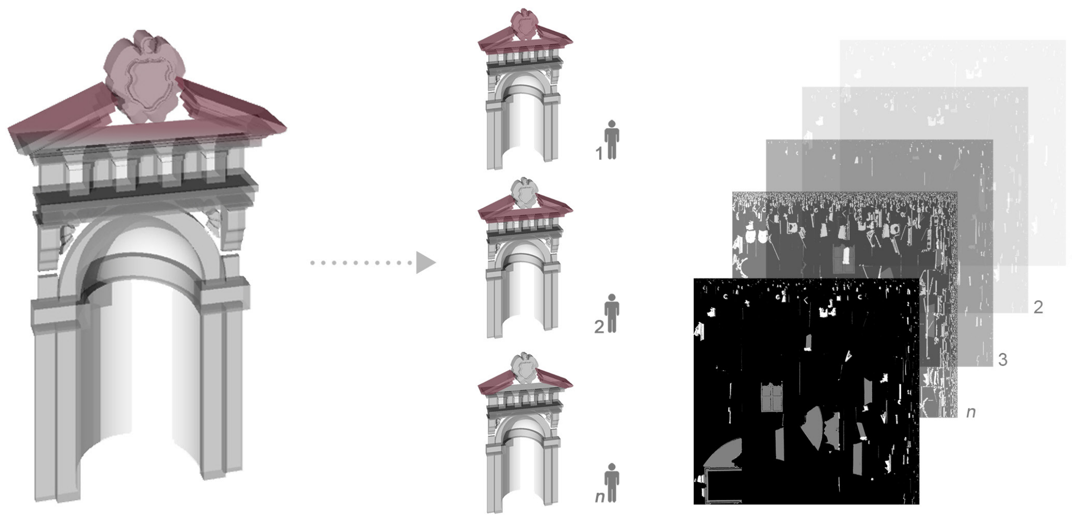

Fig. 3 - Uncertainty of annotation. Example of the coded annotation method

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and analysis of built heritage, each with its own know-how. The theorized model then allows to consider the semantic maps produced by several annotators to obtain a final map by computing the average values for each UV coordinate (fig. 3). The "weight" is gathered buy calculating the degree of agreement between the annotations of the experts, who are free to apply uncertain meanings during the labeling process. Thus, the subjective evaluation is reduced to an organised numerical scale (Cera, 2018b). (V.C.)

4. METHOD TESTING

To evaluate the validity of the theorized approach, the protocol was formalized and tested by organising a workshop in annotation application sessions carried forward by a group of domain experts on a selection of architectural concepts linked to some survey samples.
In a first phase, the experimentation was focused on the annotation of historical architecture examples, characterized by classical orders (Doric, Ionic, Corinthian, ...).
14 experts in the architectural domain, with different specializations, were recruited: 2 restorers, 2 architectural historians, 2 art historians, 2 survey experts, 2 geometry experts, 2 technologists and 2 designers. Each expert was asked to annotate 10 related architectural concepts - including, for example, capital, shaft, pediment - on digital model of classical inspiration and/or origin architectures, by the method of "painting" described above.
In order to exclude from the semantic maps computation the errors related to the different confidence with the labeling system, the painting=selection process was always carried out by the same operator, external to the group of annotators, on the basis of specific indications provided by the individual expert involved in the session.
The annotators were classified with the following labels:
Re, for restorers [2 experts, Re1 and Re2];
Sa, for architectural historians [Sa1 and Sa2];
St, for art historians [St1 and St2];
Ri, for survey experts [Ri1 and Ri2]:
Ge, for geometry experts [Ge1 and Ge2];
Te, for technologists [Te1 and Te2];
Pr, for designers [Pr1 and Pr2].
Each annotator worked to record 10 semantic maps, one for each concept taken in account, so as to collect 14 different maps for each concept.
The average between the individual maps was computed, to produce a single final map, representative of the domain experts degree of agreement with reference to a specific semantic concept.
The procedure was carried out in MatLab, by writing a specific script.
Through the 'mean' function, the software displays each semantic map as a matrix of dimen-

	Ge1_C04_bmp	Ge2_C04_bmp	Pr1_C04_bmp	Pr2_C04_bmp	Re1_C04_bmp	Re2_C04_bmp	Ri1_C04_bmp	Ri2_C04_bmp	Sa1_C04_bmp
Ge1_C04_bmp	1,0000	0,9859	0,6434	0,6550	0,0175	0,2873	0,7705	0,8680	0
Ge2_C04_bmp	-	1,0000	0,6502	0,6625	0,0188	0,2907	0,7790	0,8505	0
Pr1_C04_bmp	-	-	1,0000	0,4637	0,5276	0,6905	0,5467	0,5190	0
Pr2_C04_bmp	-	-	-	1,0000	0,0163	0,0174	0,8854	0,7055	0
Re1_C04_bmp	-	-	-	-	1,0000	0,8835	0,0191	0,0230	0
Re2_C04_bmp	-	-	-	-	-	1,0000	0,1002	0,1513	0
Ri1_C04_bmp	-	-	-	-		-	1,0000	0,8297	0
Ri2_C04_bmp	-	-	-	-		-	-	1,0000	0
Sa1_C04_bmp	-	-	-	-		-	-	-	1
Sa2_C04_bmp	-	-	-	-		-	-	-	
St1_C04_bmp	-	-	-	-		-	-	-	
St2_C04_bmp	-	-	-	-		-	-	-	
Te1_C04_bmp	-	-	-	-		-	-	-	
Te2_C04_bmp	-	-	-	-		-	-	-	

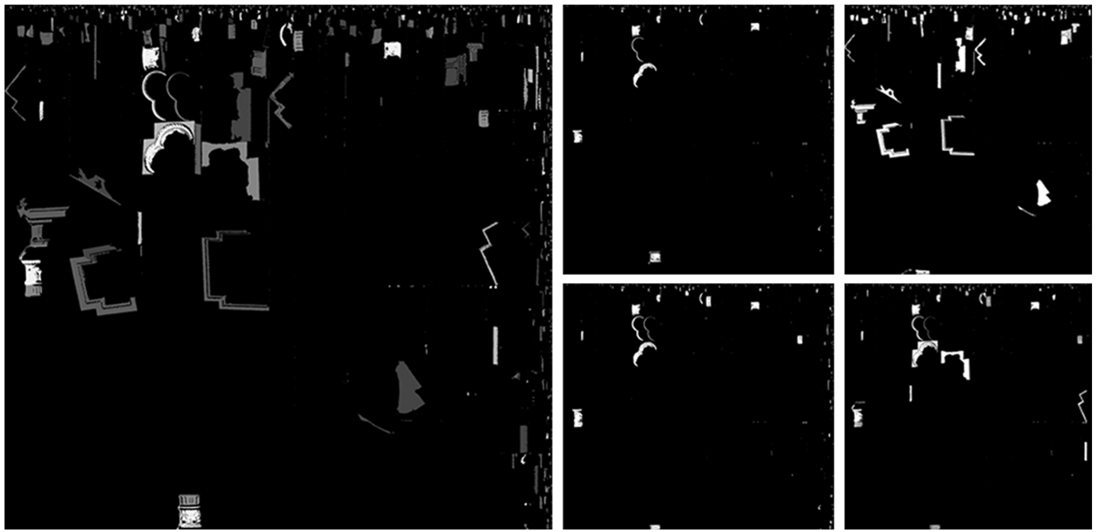

Fig. 4 - Classical architecture. Calculation of the semantic map as level of agreement between the annotators (concept of capital

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sions m x n, whose elements are integers, 0 or 1, and calculates the arithmetic mean for each pixel occupying the same position in all maps. The results of the calculation are written in a new matrix, corresponding to a grayscale image, whose size is always defined by the m x n pixels of the m rows and n columns. The matrix elements take, this time, values in the range from 0 to 1, which are the average for each UV coordinate of all 14 maps included in the calculation.
Simultaneously with the computation of the final map in shades of gray, the software evaluates the degree of agreement between the annotators, carried out by calculating the correlation coefficient. The 'corrcoef' function returns the matrix of Pearson's correlation coefficients, i.e. the linear correlation of two variables. The semantic maps, produced by the annotators for each single concept, are computed two by two. The correlation function evaluates whether the two maps, the two random variables, change together in a linear way. The closer to 1 is the coefficient value, the more the two measurements change together by the same amount. Therefore, the two annotators agree [3] (fig. 4).
Aiming to broaden this reasoning, the research was deepened with new annotation sessions concerning architecture examples not exclusively related to the application of the rule of classical orders but representative of historical heritage. The aim has been (and is not yet exhausted) to verify whether the annotation uncertainty is actually ascribable to a specific segment of the historical heritage, for example: the classical world, or whether the question is broader.
Once again the domain experts were recruited, according to the logic of specializations already expressed. This time the individual sessions focused on the annotation of concepts linked to case studies selected in reference to two fields, religious architecture and fortified architecture. (V.C.)

5. RESULTS DISCUSSION

The results of the first annotation session focused on classical architecture (partially published in Cera, 2019b) showed how the domain experts specialization determines a vision and interpretation of the same architectural object that we could define "categorized". In isolating the classical concepts, restorers preferred observations about the static behaviour of the architectural score, choosing the forces and loads system distribution scheme as a key element of discernment. On the other hand, geometers and surveyors based their annotations on the identification of the geometric processes of spatial forms generation and on proportioning criteria (fig. 5).

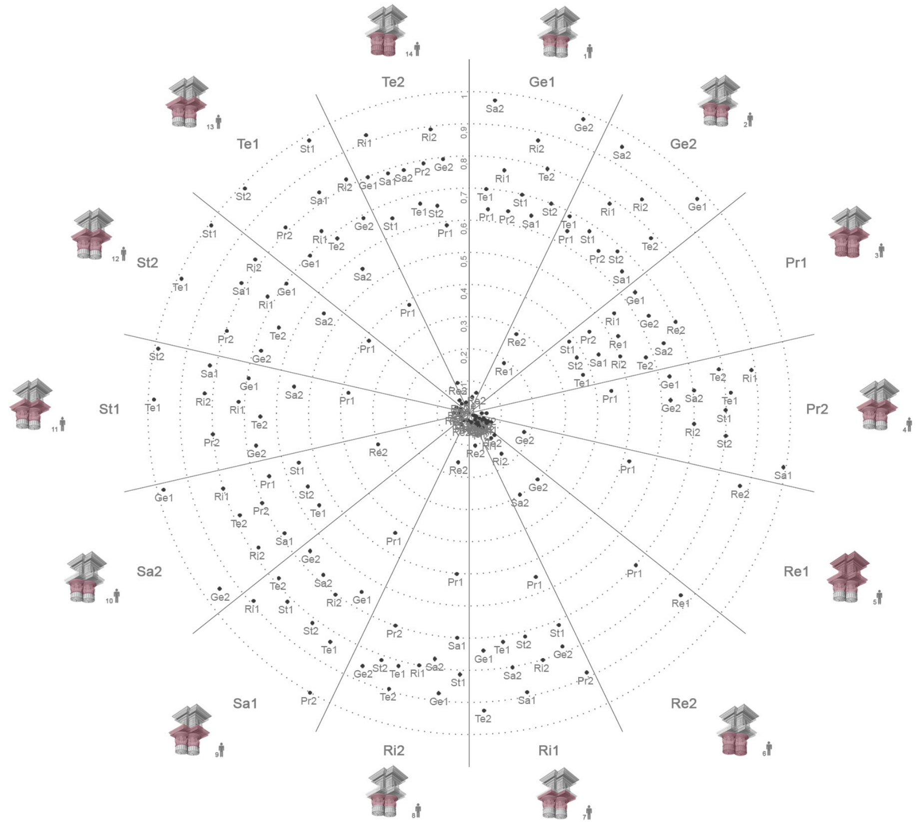

Fig. 5 - Classical architecture. Calculation of the agreement degree between the annotators (concept of capital)

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The thoughts gathered from the second experimentation session were different and revealed more complex situations.
Specifically, for the fortified architecture, the uncertainty of the annotators was minimal and therefore their degree of agreement was almost complete. The only concept on which significant disagreement has arisen is the 'torretta', that was variously identified on the sample model (fig. 6). The analysis of the results shows that the different recognition of the corresponding architectural element was generated by a lexical ambiguity. The use of the lemma 'torretta' by the test administrator in place of 'torre' has probably led experts to figure in the search for the associated spatial concept, a component of reduced size. The ambiguity is entirely linguistic since 'torretta' is a polysemic lemma. In some contexts, its meaning has been interpreted in relation to that deriving from 'torre' through an alteration phenomenon, that is the formation of words starting from others for which their fundamental features are not modified, but rather the concept that one has of them (augmentative, diminutive, etc.). Another interpretation is related to the meaning that is created by semantic extension through a lexicalization phenomenon, whereby a sequence of characters is attributed to a concept, thus ending up representing an autonomous lexical unit in comparison to the one from which it originates.
The results obtained from the examination of the annotations on religious architecture were different. The decomposition of 3D representations into significant elements according to a vocabulary proper to sacred architecture has revealed another important aspect, once again closely linked to the background of the annotators.
In the confinement of concepts such as presbytery, choir, etc., experts have revealed differences in the ability to visualize and conceive the architectural space in its three dimensions (fig. 7). Historians tend to work in a bidimensional way, often leaded by decorative aspects. This is different from what technologists and designers usually do, trained in a vision of architecture interpreted in its spatial extension, shaped, for the second category of specialization, on symmetry, alignment and distribution criteria.
The last point on which the research focused on is verifying the existence of categories of experts that have a greater degree of agreement in classifying and segmenting architectural elements, to highlight which specializations contribute the most in enriching the semantic reasoning about such forms.
The experimentation revealed that, although carried forward on a still small sample and therefore to be expanded and deepened, the closest profiles in cognitive processes are the geometers with historians and technologists, among whom the degree of agreement is close to unity; and technologists with survey experts, whose affinity fluctuates around 0.9. More distant are the points of view of designers and even more so of restorers who, with previous specializations, show an agreement level sometimes as low as 0.2 (this is the case of the evaluation made for the concept of 'pediment'). (V.C.)

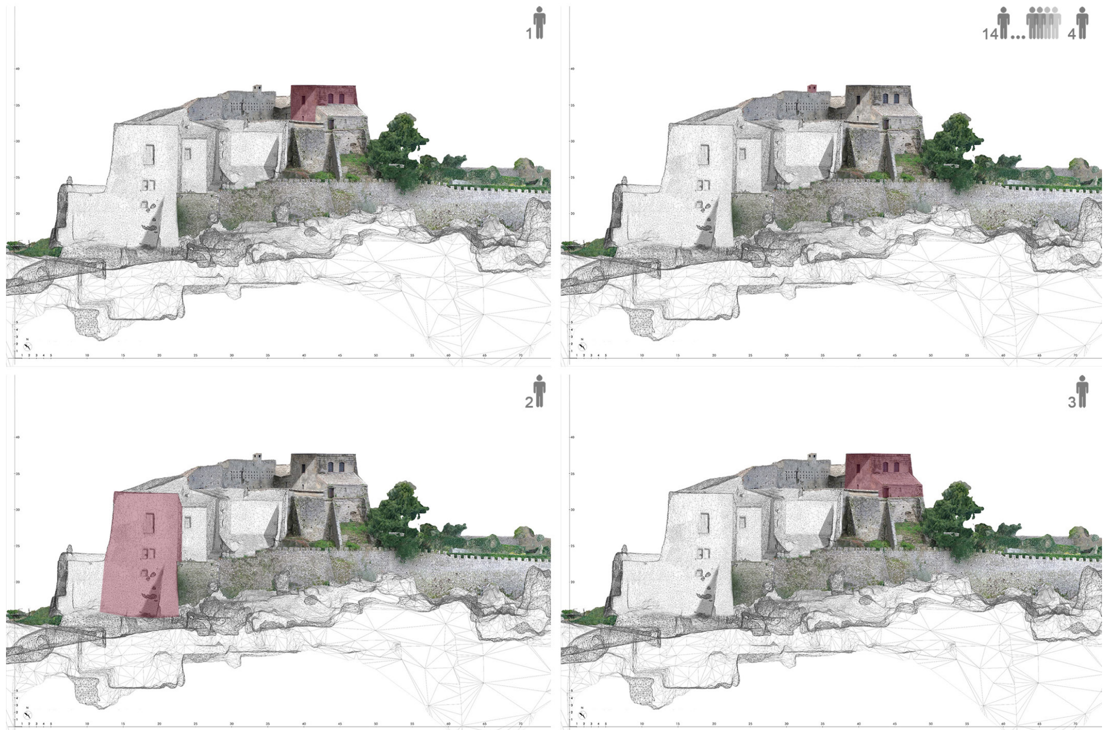

Fig. 6 - Fortified architecture. Annotation examples for the "torretta" concept

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6. CONCLUSIONS

The research presented in this paper shows that the uncertainty of semantic annotation, widely motivated at the beginning of the discussion, is intimately linked with the different specialization of the expert annotators. They, once called to gather concepts of the specific domain of historical construction with the related spatial forms, show a real uncertainty of segmentation intended as identification of the boundary of the examined element. Their uncertainty is motivated by specific training which exercises a clear influence in the approach of interpretation and discernment of significant architectural forms.
This aspect was revealed through the experimentation whose results have been showed here.
In order to transform the semantic structuring uncertainty from problem to resource, the study formalized an annotation protocol capable of recording the uncertainties of the annotators and measuring their degree of agreement.

The discussion results, albeit in the still small number of samples collected, made it clear that it is not possible to directly translate the geometric segmentation logics to mathematical algorithms in order to objectify the semantic structuring operation due to the different points of view and criteria with which the cognitive process is led. In addition, the uncertainty and subjectivity of annotation does not seem isolable to a specific segment of the historical building but the question arises with wider boundaries and in need of deeper thoughts.
There is no doubt that the resolution of the annotation uncertainty with the proposed method allows the involvement of all the variously connected specialists in the process of knowledge and dissemination of the architectural cultural heritage, without however bending the professionalism to superordinate points of view, preserving and enhancing, quite the opposite, the investigation and views specificities. In this way, the semanticized architectural representations really manage to be a support for knowledge, sharing and document enrichment, avoiding the need to have as many different models and lexicons as the experts who query them. (M.C.)

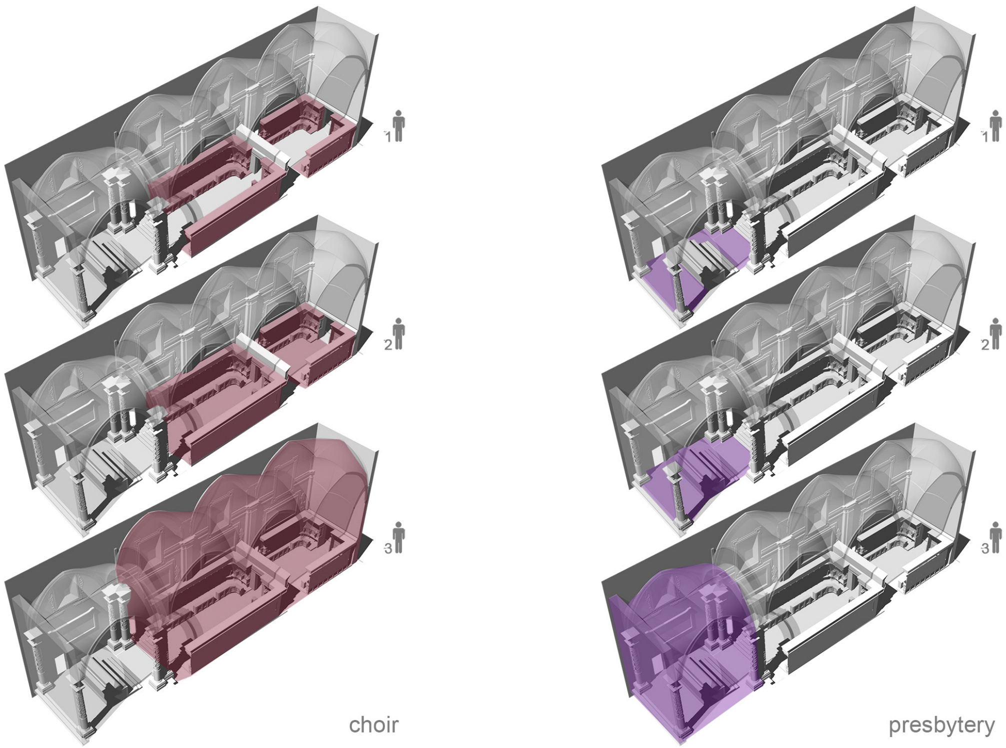

Fig. 7 - Sacred architecture. Example of experts' ability to visualize and conceive the architectural space in its three dimensions

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NOTE

[1] The Art and Architecture Thesaurus of the Getty Institute was chosen for the selection of the domain words.

[2] This is Adobe's Substance Painter software used for texturing 3D digital elements.

[3] In theory, the extremes of the computation interval are -1 and 1 because Pearson considers the possibility of a linear but inverse correlation. In the research, the interval was reduced to 0 and 1 since only direct linear correlations are of interest.

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