ISSN 1828-5961

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Semantic-driven analysis and classification in architectural heritage

In the Architecture domain, the study, comparison, connection of morphological properties and meaning in a knowledge domain are crucial for building analysis. According to their spatial and functional hierarchical system, the formal complexity depends on the relationships and inferences between shapes. Digital technologies open today new opportunities for the cross-analysis of many cultural heritage artifacts, afar in space but close in features (typologies, styles, compositional rules), stimulating the creation of innovative scientific frameworks. The architectonic shape investigation involves different cognitive processes based on traditional and digital methods. The definition of experimental paths to study these forms and their hierarchical relations is an open topic. Combining theoretical knowledge with technological evolution is a crucial challenge today within the trending topic of the digital humanities. It moves towards a sustainable framework to merge human-driven interpretation and computer-based massive analysis within cross-disciplinary approaches by introducing sustainable paths of methodological renewal. This goal shifts the focus to analysing architectural heritage's geometric nature, representing the core of this journal issue.
How did the authors of this issue interpret this specific topic? How has morphological analysis, regarding geometry and semantics, been declined for architecture investigation and interpretation? In Architecture, shape grammars cover a primary role in defining and understanding complex objects, behaviours, and transformations, like the bricks of a wall or the words in text composition. In this sense, a first statistical analysis of text repetitions in the articles may lead to a first idea about the contents and the topics developed, correlating the authors' keywords with the papers' whole text. The first cloud of words (Fig.

Keywords:
Semantic-driven analysis; multi-criteria classification; architecture; shape grammars; data Interpretation; knowledge-based process

DOI: https://doi.org/10.20365/disegnarecon.26.2021.ED

ISSN 1828-5961

1) raises the prevalence of case studies related to Architecture and Cultural Heritage. These two terms present a significant overlap, both closer to Built Heritage. Besides, a challenging prospect foresees the enlargement to the Cultural Heritage domain, encompassing tangible, intangible, natural aspects for a broader and more extended semantic meaning. Next, the primary forms of representation used for the analysis in the domain (point clouds, Building Information Modelling, parametric models) appear alongside the two most recurrent activities (survey and modelling), integrated by some data processing activities required in the issue (classification and optimization, annotation, and semantic description).
The transition to the objective word cloud (Fig. 2), merging all the issue texts, shows some fascinating aspects. The first one highlights the centrality of the model role, intended as a form of reality interpretation at different levels of simplification. The model is the primary analysis tool and an instrument of knowledge and understanding reality. It also represents an extraordinary witness of historical continuity (towards the technological evolution) of the scientific foundations of architectural representation. It is demonstrated by the recurrent verb "use," which refers to an active application of instruments and extracted data within a technological framework. Furthermore, the Architecture domain's primacy is evident compared to Cultural Heritage or Built Heritage ones. Finally, the main model declinations (points, digital data, BIM), relating to the geometric representation, are strengthened with minor influence on model subdivision activities or morphology understanding processes.
It is interesting to deepen the relationship between architecture, the geometric nature of shapes, and how they are presented in the papers. Architecture finds in geometry representation its privileged instrument of reading. In the same way, geometry finds in architecture one of the preferential channels of experimentation. Architecture and geometry are firmly unified by the concept of scale, defining a tree structure development that fixes connections, relations,

Fig. 1 - Word cloud obtained from keywords.

Fig. 2 - Word cloud obtained from paper text.

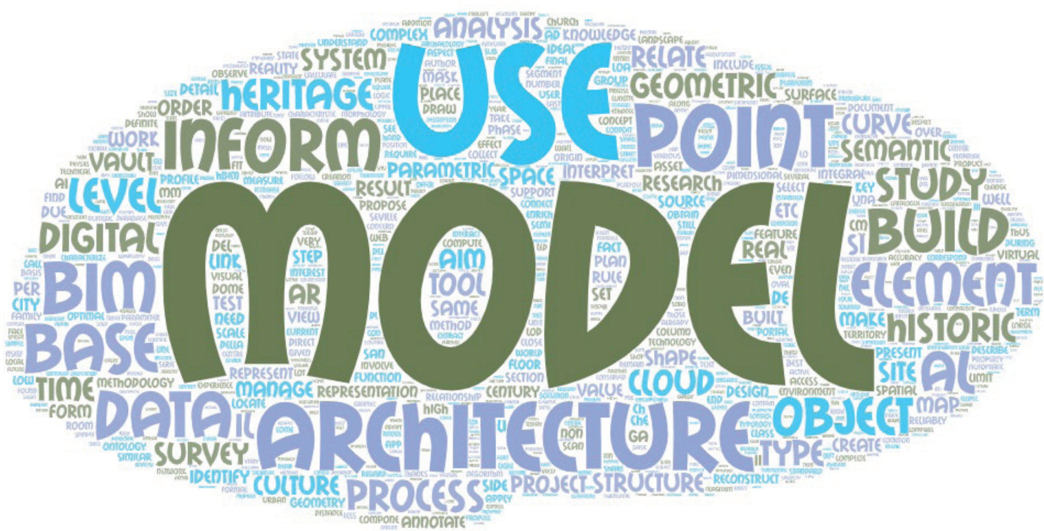

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Fig. 3 - Paper distribution schema according to domain, scale, analysis process, and topic covered.

similarities, repetitions. The shapes recurrence, the research of similarities between different architectural signs, and the functional and formal dependence relationships highlight a clear hierarchical structure. It binds the overall system with its components, defining an order of reading. The scalability of this analytical approach, the interpretation, and the creation of new shapes allow understanding and suggest semantic-aware representation of decorative details, architectural portions, architectural or archaeological artifacts up to a territorial context, and urban developments. The articles presented cover all these fields, showing a particular interest in the architecture domain (Fig. 3), as anticipated by the word clouds. Some research presents borderline domains because the case studies allow different reading levels, or the methodological approach requires to test case studies belonging to different fields. Most of the contributions fit into an exact domain, analysing a single case study. Only one research analyses three different domains and scales.

The article's clustering in the research framework has considered the application domain and its scale of analysis, highlighting both the process steps and the research topics. Regarding the applied methodological path, it is evident that the focus of the research is mainly shifted to the data modelling and interpretation phase. The 2D/3D data acquisition process is exhaustively described in a small part of the articles, while most of them, although mentioning it, start from 2D/3D data collected. That is justified by the awareness of the actual minor research challenges in surveying and data digitization compared to data management and interpretation ones. Besides, only a minor part of the research proposes platforms or representing instruments despite their critical roles in communicating and processing data. This first research framework is confirmed by the subdivision of the articles in the issue topics. Although some articles are borderline between more than one research area, knowledge-based 3D imaging is poorly covered. Most articles focus on semantic modelling methodologies, comparative analysis, and multi-criteria classification. Besides, also AR/MR and AI topics are little discussed. The first one supplies an answer to the representation and communication lack, highlighting the complexity in designing systems to augment and interact with built artifacts (by intersecting the overall surveying-modelling-representation chain). AI presents considerable potential in data management and representation, but it requires specific skills that need multidisciplinary approaches even more than the AR/MR theme.

Moving into the individual research themes proposed by the issue, the first topic deepens the research beyond the generation of accurate reality-based 3D models, creating an interpretative geometric representation of architectural shapes. A knowledge-based 3D imaging approach has a critical role in representing architectural elements and their geometric nature. The authors interpreted the topic focusing on different as-

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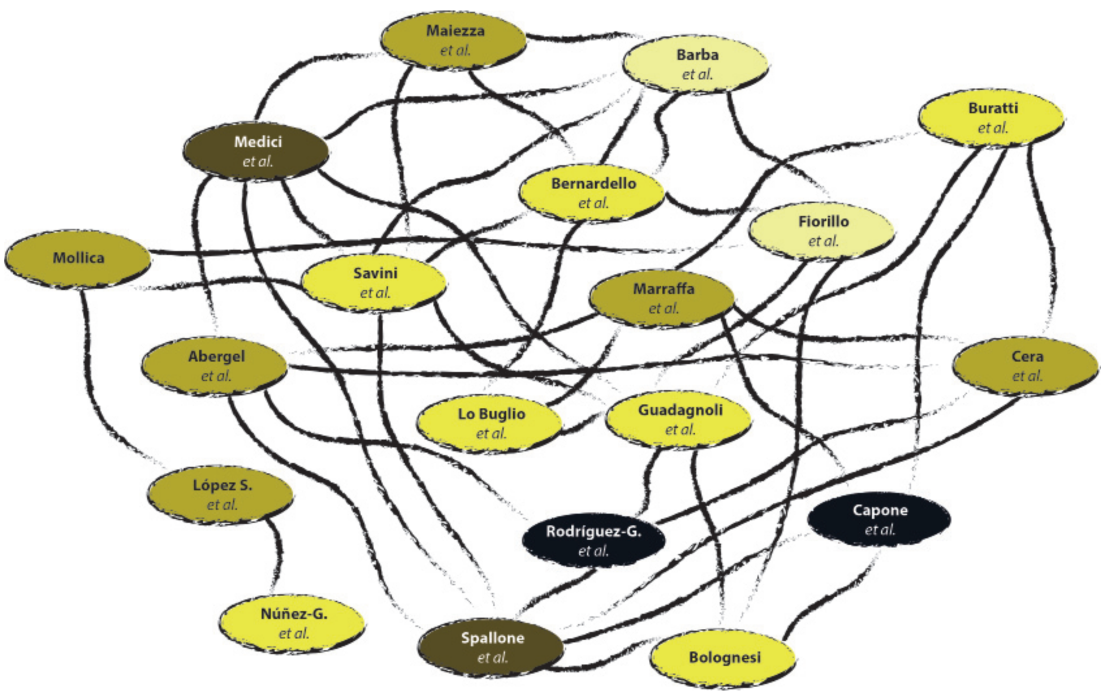
pects, from environment knowledge to recurring elements, from Scan-to-BIM optimization to reality-based point-cloud reliability, suggesting a traceability approach. Barba et al. deepen 3D data quality in a Scan-to-BIM process for the architecture documentation in a controlled environment. The research aims to introduce in a general pipeline the quality control parameters in an unambiguous and standardized way, extending the interoperability of 3D BIM models. Besides, Fiorillo et al. shift the interest from architecture to archaeology, focusing on recurring elements and shapes similarities to support digitalization and modelling activities, applying Scan-to-BIM optimized approach to represent architectures that no longer exist.
The second topic is devoted to the construction process of a new generation of semantic-aware digital models. Specifically, the topic involves research on shape grammars, parametric modelling, multi-purposes interpretive models, and the formalization of historical knowledge. A hierarchical approach based on recurring 2D/3D features is critical to understanding reality. Semantic modelling methodologies support the research in this domain for interpretation and data integration at different scales. Lo Buglio et al. identify distinctive "firms" in the survey data, suggesting a semi-automatic architectural element classification. Furthermore, they investigate the morphological/semantic characterization of architectural shapes according to different scales of observation and based on the exploitation of massive data. The transition from real to digital data concerning the source signs is also present in Núñez-González et al. 2D data interpretation, 3D model generation, typological clustering, suggest a virtual representation of hundreds of buildings framed in a historical urban context. In addition, the database created is also helpful for historic map generation and typologies analysis. Moving to the architectonic scale, the geometric analysis, and the comparison between state of the art and ideal shapes suggest a hypothetical original version of the artifact, deepening a critical reading. That is the case of Bolognesi's research, which focuses on the built vault, verifying precise geometry compared to the existing form. These parametric models start from the shape grammars, feature repetition, identifying possible symmetries, eurythmics, matrices. In this sense, fractals geometry is suitable for explaining these recurrent phenomena' scalability in the plane and space. Generative algorithms may support the modelling step, creating complex shapes almost present in nature but often recalled in the Architecture domain. Buratti et al. explore computational processes in design to describe and control model complexity factors, managing recurrent elements repetition. The recurring to almost simplified geometric shapes and the interconnection between different elements are distinctive aspects of the BIM platform. According to a semantic structure, the geometric analysis, shape optimization, and re-generation suggest classified models, reinforcing the relationships between model container, data contents, and users. Guadagnoli et al. suggest a helpful prototype for the communication of Cultural Heritage. They deepen the relationship between the modelling activity and the user cultural experience, remarking the role of 3D hierarchical data to improve historical/cultural heritage. The hierarchical classification of a single column system can be extended to the whole architecture framework, identifying the relationships of constructive dependence. The ontologies in the Architecture domain help organize the data coherently, using

Fig. 4 - Research works connections schema.



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precise definitions and descriptions of the relationships between different elements. Bernardello et al. describe this process in the BIM platform, suggesting an interoperable platform between experts in representation and architecture history. The semantic trees can be helpful to relate singularities with the whole, as well as boosting the comparison between single features. The latter requires the construction of typological abacus and shape databases for comparing similar elements. Following this research line, Savini et al. start by surveying, modelling, and comparing historical portals. They suggest an HBIM platform (3DIIS) that simplifies data management and interoperability, encouraging fruition by AR/MR and supplying protection activities for the valorisation of historical centres.
The third topic shifts the focus to model exploitation through data analysis, management, and simulation, paying attention to the uncertainty level that may affect some passages. Specifically, experimentations related to comparative analysis and multi-criteria classification methods, tools, and applications have been encouraged, suggesting innovative cross specimens' relations, and constructing a semantic-driven system of knowledge.
At urban and territorial scales, the analysis is developed through cartographical representations. Data classification is more related to thematic networks than ontological structures. López Sánchez et al. present a methodological approach for diachronic landscape analysis, cartographic production, and emergencies network definition. It supplies on one side landscape data management, enhancing the social use of the territory and supplying cross relations between homogenous heritages. Architectural emergency's location on a territorial scale can also strengthen their network, understanding the constructive genesis and these architectures' role with the environment. In such a sense, Mollica suggests a replicable methodology to reinforce lighthouses network framed in the Mediterranean basin. A preliminary shape and typological analysis define interoperable models, improving restoration, reuse, or fruition activities. The construction of morphological and typological abacuses helps classify and cluster specimens according to specific variables at all scales, favouring comparison activity. This last step can provide a fundamental contribution in understanding stylistic features and the interpretative reconstruction of missing parts. In that sense, Marraffa et al. propose a protocol for identifying the genealogical and filiation relationships between theatrical masks fragments to restore their memory, following a scalar and hierarchical workflow based on the geometric description, annotation, and semantic segmentation. The research suggests improving the segmentation step in the Aiolì platform to support the classification activity. These platform capacities are well described in the research of Abergel et al., who introduce the paradigm shift given by outsourcing ex-situ most of the analysis activities. They suggest an integrated approach based on the fusion of geometric, visual, and semantic features in a single multimodal platform, ensuring the continuity of in situ and ex-situ works. The application allows generating semantically enriched digital data, developing effective visualization, and optimized classification procedures.
The semantic structures present the essential variable of annotation uncertainty. The decomposition into single elements with a specific semantic description is typically carried out within a rigid concept and topological interactions between solid instances. However, this activity is hardly suited to the historical heritage complexity, and it depends on the different specialization of the expert annotators. Cera et al. discuss this critical passage, suggesting an annotation protocol capable of recording the uncertainties of the annotators and measuring their degree of agreement. Data uncertainty and reliability represent a critical issue also in the generation of hierarchically structured complex systems. This aspect emerges in the phase of geometric acquisition, classification, and data annotation. However, it also assumes an essential role in the construction and visualization of the 3D model. The 3D model reliability must introduce a specific visual connotation, then concurs to estimate an aware use of the model. Maiezza et al. focus on the "transparency" of information sources and the modelling reliability, suggesting a methodological approach that fixes the model sources, visualizes the digital reconstruction's reliability level, and defines a relation between data reliability and Level of Detail (LoD).
Data representation, interaction, and virtual immersion are central in the knowledge process, even if often integrated within the survey, modelling, and visualization pipeline. The combination of AR and MR tools in situ allows reaching a more immersive visualization, improving the analysis of the real world. For this reason, a separate research topic has been devoted to AR/MR approaches for geometric shapes in-situ analysis, understanding, and storytelling. As pointed out in the introduction, data visualization and communication have been less investigated by the researchers. Nevertheless, some of them prefigurate their use in the future. Besides, others show real applications but framed within a more complex pipeline in which visualization is not central. Two research projects emphasize using AR/MR/VR/AI tools to communicate and interact with Architecture. Spallone et al. present different research experiences dealing with AR and AI technologies for built heritage understanding. AR is applied to enhance the accessibility and communication of documentation and 3D interpretative models of vault systems. A Deep Learning approach allow monument recognition in archaeological and urban sites. At last, the fusion of AR and AI prefigurates the improvement of structured spatial databases, such as BIM. A different approach is offered by Medici et al. They start from interoperable BIM models collected on a cloud-based platform, presenting the integration of AR and MR tools for the built Heritage management, control, interaction, supporting the restoration, conservation, and maintenance activities.
The experimentations so far have described geometric analyses at different scales of representation, proposing methodological approaches to define homogeneous clusters of recurrent shapes and organization in hierarchical infor-

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mation systems. Most methodologies involve a manual contribution, with direct responsibility in data interpretation, with massive investment in man/time hours. Some researchers suggest an image recognition approach to optimize the procedures of shape segmentation and classification. This research domain is less explored in the analysis of spatial geometries. The object's shape analysis frequently involves interpretation of similarity metrics, in which AI is opening new scenarios in the massive analysis, classification, and morphology segmentation. For that, the last research topic is devoted to innovative AI experiences for the classification, annotation, and segmentation of architectural models. In such a sense, two different experimentations show inspiring examples of AI applied in the Architecture domain. First, Rodríguez-Gonzálvez et al. present a point clouds classification methodology related to architectural portal based on dimensional features. The approach uses geometric features and a Machine Learning approach, suggesting the automatic classification of the 3D point cloud. It preserves the geometric quality for reality-based modelling, optimizing the real-time visualization of complex models. The latest research proposed by Capone et al. move from Point Cloud Semantic Segmentation to 3D modelling, recommending a process to study and optimize geometric shaping in space. The core of this activity is the analysis of domes' geometric nature, showing the automatic generation of geometric solutions. It refers to techniques inspired by natural evolution, finding 'semi-ideal' or ideal analytic curves that best fit and decode complex elements. The approach opens future collaboration scenarios between man and computer in the critical passage of geometric interpretation and graphic restitution of complex shapes.

In conclusion, it is possible to glimpse an underlying research network of relationships between contents and methodologies proposed. The topic developed, the research domain, the methodologies of analysis employed, and the affinities in the objectives suggest some intersections between research and authors through a qualitative critical analysis (FIg. 4). The connections highlight a cross-topic system in which the authors have supplied a specific contribution to a broader knowledge system. Research at the territorial scale presents fewer connections because it is borderline for the call. On the contrary, the articles that dealt with the complexity of architecture, analysing its hierarchical aspects, connections, and grammar shapes, present many connections. The same is also confirmed for research focused on visualization with AR/MR/VR systems, which assign a central role to the communication aspects of the model. On the other hand, research on AI is less connected because, while scalable, it supplies an optimal response to a specific research aspect. Starting from this frame, some scenarios can be envisioned. The research scope in the domain should move toward a wider variability of scale and context of the application, expanding both to the constructive aspects and to immaterial cultural topics. Automatic or semi-automatic methodologies for data processing and interpretation will play an important role in the research, but it will essential the supervision of experts in the domain to guide the process and verify the obtained results. Finally, the transdisciplinary nature of the topics covered by the issue shows the importance of integrating skills. They can define a network of knowledge that provides deep answers to increasingly complex problems, to be explored by new analytical approaches fostered by computational methods. This last point highlights the need for a sustainable articulation of human-driven analysis and computer-assisted processing able to sketch the next generation of methodological approaches for producing new scientific knowledge on Architecture and Cultural Heritage.

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