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Facing the complexity. Digital tools in *transformation* toward heritage cognitive-interpretative approaches through graphical representation

The rapid evolution of digital surveying technologies and AI-based tools is reshaping discretisation processes in architectural representation, introducing new modes of data acquisition, analysis, and interpretation. In this context, however, the construction of knowledge remains inseparable from a methodological framework grounded in hierarchisation and interpretation that are intrinsic to surveying and representation. Whereas in the analogue tradition these operations were embedded within the very act of drawing as a discrete practice, in digital processes, they become fragmented and therefore require explicit critical and epistemological clarification. Within this framework, automatic segmentation emerges as an effective tool for the local classification of surfaces; however, it reveals significant limitations in reconstructing the geometric, spatial, and constructive relationships that shape architectural language. This contribution addresses these critical issues through the application of deep learning models for the semantic segmentation of masonry textures, focusing on the case study of Palazzo Costabili in Ferrara. The model, trained on datasets generated through supervised annotation processes, aims to evaluate its capacity to recognise and organise recurring morphological characteristics in masonry structures. One the main research questions is related to the chance to reconstruct, through segmentation, complex configurations as organised systems, leveraging on interpretative choices embedded in the annotation process, analysing automatic recognition and classifications towards a critically meaningful structure of graphic representation and knowledge drawing.

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Graphic discretisation; AI-Driven representation; Semantic Interpretation; Digital surveying; Heritage documentation

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INTRODUCTION

Graphic discretisation, within the field of architectural representation, founds the process of identifying, classifying, and interpreting elements of reality through signs. Drawing functions as an immediate device that translates information and meaning into forms that support the documentation and understanding of a building and, in turn, orient project actions.
In traditional practice, the measurability and representability of reality were achieved simultaneously with the survey project, through the materialisation of relevant points. The introduction and widespread adoption of advanced surveying and drawing technologies have profoundly transformed this process. The extensive and indirect acquisition of spatial data has shifted the discretisation phase to a process following data capture, requiring direct intervention on the point cloud to identify and define the model's significant elements (Bianchini, 2014).
Today, the rapid expansion of computational processes and data-driven imaging technologies places the discipline of drawing within an advanced stage of methodological transformation, as highlighted by recent studies on the *Digitocene* and on the emerging condition of the *InfoSapiens* (Giannini, 2024). Although the integration of Artificial Intelligence (AI) tools and advanced surveying techniques has become the focus of several experimental investigations, their methodological systematisation still demands critical and informed coordination. In this context, drawing must redefine its research methodologies, negotiating between disciplinary traditions and newly established forms of computational knowledge. Ethical reflections on the *Infosphere* (Floridi, 2020) and analyses of epistemic responsibility (Cosenza et al., 2023) provide a conceptual framework for questioning the nature of data and images produced by algorithms, underscoring the need to integrate standards of transparency, verifiability, and traceability into visual processes. Likewise, the framework of "multiple intelligences" (Gardner, 2025) underscores the importance of recognising the multiplicity of competencies involved in drawing (visual, analytical, spatial, narrative, and technical), as elements of an integrated methodological approach.

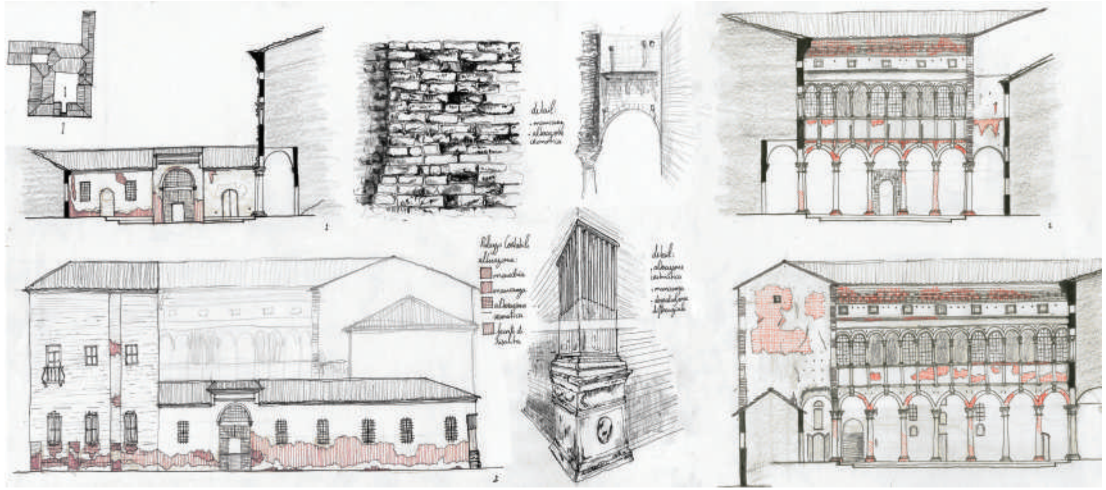

Fig. 1 - Primary sketching stroke is hierarchically articulated through processes of selection and systematisation of information, aimed at a synthetic, hierarchically organised representation. Graphic elaboration by the authors.

When applied to heritage documentation within the geometric-spatial and analytical-semantic categories of knowledge, AI techniques often rely on supervised learning models for the classification and segmentation of large datasets derived from digital surveying (point clouds and/or images) (Mazzacca et al., 2025). Discretisation and semantic attribution must be undertaken by expert practitioners whose domain knowledge and critical-interpretative sensitivity (qualities that resist objectification) play a decisive role in both manual annotation and the validation of automated results (Parrinello & Pettineo, 2025).
Within this hybrid analytical scenario moving between analogue (Fig. 1) and automatic processes, this paper examines AI-based methods and tools to assess the possible levels of "decomposition", analysis, and discretisation of the morphological and surface features of historical-architectural heritage systems characterised by complexity and stratification. The aim is to translate these features into critical-interpretative representations that rule the relationship among survey-derived data, analytical objectives, and the chosen scales of representation. To support this methodological reflection, the paper presents ongoing applied experiments designed to identify potential ontological and semantic-representational trajectories that may be achieved through "autonomous" processes. Within this framework, drawing is conceived and deployed as both a critical device and a validation interface.

DISCRETISATION AS AN EPISTEMIC ACT

In the processes of surveying, documenting and representing, when selecting, distinguishing, emphasising or omitting, the practical-cognitive operation carried out is not limited to recording

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reality, but is defining an interpretative structure. The graphic line incorporates hierarchies, spatial relationships, depth and temporality; the differentiation of thicknesses, shadows, lines and backgrounds already translates an understanding of the surveyed space (Bini, 2017).
Discretisation, therefore, does not come after observation, but coincides with it. The act of drawing is simultaneously analysis and synthesis, measurement and interpretation. The choice of what to represent and how to represent it is already a form of structured knowledge, referred to a purpose and a scale of representation (Docci & Migliari, 1992).
In the field of architectural representation, graphic discretisation is a process that simultaneously involves the selection, classification and interpretation of reality through systems of signs. From this perspective, drawing does not function as a mere descriptive transposition, but as an operational tool capable of organising spatial information and making them legible and understandable through relational structures.
With the evolution of digital surveying techniques, this process has undergone a substantial transformation. The massive acquisition of data through point clouds and images has progressively separated the act of measurement from that of "constructing" meaning, shifting discretisation to a phase following acquisition (Bianchini, 2014). In this transition, the identification of significant elements is no longer implicit in the act of surveying but requires explicit operations of interpretation of the digital data.
The implementation of Machine Learning (ML) and semantic segmentation systems has further transformed this scenario. These frameworks operate by recognising local patterns and statistically classifying discrete units, demonstrating high performance in the precise identification of elements. However, this local effectiveness is not matched by a truly comprehensive ability to reconstruct global relationships: neural networks indeed do not process the geometric and structural continuity of the architectural shape, nor are they capable of reliably interpreting spatial discontinuities such as projections, off-plane elements or complex volumetric variations. The result is a representation in which projective and three-dimensional relationships are implicitly weakened or unrecognised.
The effectiveness of such models depends highly on the structure of the training dataset. This, through supervised annotation processes, involves a selection and structuring of the data deriving directly from expert knowledge, transferring an interpreted taxonomy into the model. In this sense, the ML process is not neutral, but reflects methodological and cultural choices linked to the definition of classes, the granularity of labelling, and the construction of the semantic hierarchy (Inglese & Lucchetti, 2022).

RENAISSANCE WALL TEXTURES AS A TEST-BED

The case study selected to explore the relationship between algorithmic segmentation and drawing is Palazzo Costabili in Ferrara. In particular, the applications focused on the representation of the masonry textures, which are varied and uneven across the different sections of the *Cortile d'Onore* (Courtyard of Honour), the main façade along Via XX Settembre and the garden façade, the setting chosen for specific examination.

Palazzo Costabili, also known as Palazzo di Ludovico il Moro, was commissioned by Antonio Costabili, Ferrara's ambassador to Milan and advisor to Ercole I d'Este. According to an undocumented tradition, the purchase of the site and the construction of the palace were carried out by Costabili on behalf of Ludovico il Moro, Duke of Milan, who is said to have decided to build himself a sumptuous residence in the hometown of his wife, Beatrice d'Este. In popular imagination, this attribution has remained in the palace's name.
Designed by Biagio Rossetti, construction began between 1495 and 1500, but in 1503 Rossetti abandoned the project, entrusting it to Girolamo Pasini and Cristoforo di Ambrogio da Milano. In 1504, construction was definitively abandoned, and the building remained unfinished (Bassi, 1994, pp. 112–113).
The Costabili family died out in the 16th century, and from 1595, a series of changes in ownership began, leading to its deterioration. It was not until 1920, on the initiative of the Director-General of Antiquities and Fine Arts, Corrado Ricci, that the State purchased the property from its last owners. Extensive actions were required to restore the structure when, in 1929, the Ministry of National Education decided to use it as a home for the archaeological finds discovered in the Spina necropolis (Caglioti, 2024). Work began in 1932 and

Figure 2 - *Cortile d'Onore* (Courtyard of Honour) and detail of the main façade of Palazzo Costabili. Photos by the authors.

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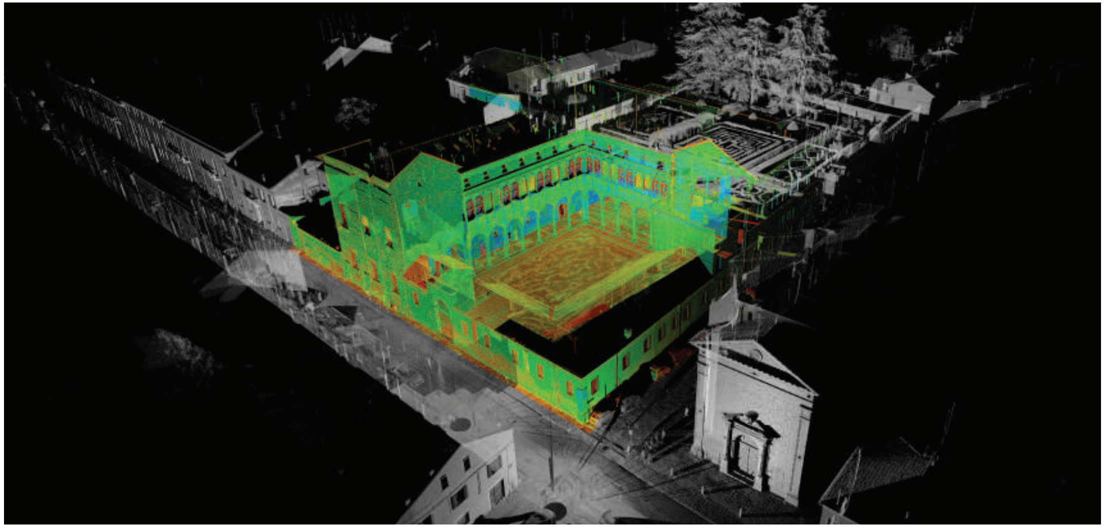

Figure 3. Laser scanner point cloud of Palazzo Costabili, general view. Graphic elaboration by the authors.

involved the consolidation and adaptation of the building for use as a museum. In keeping with the practice of the time, the original style was restored, and many Baroque decorations were removed. The most recent restoration work dates back to 1985 and continued into the 1990s.
The Courtyard of Honour at Palazzo Costabili, despite being unfinished, is the most significant space in the building, so much so that it has been attributed to Donato Bramante (Zevi, 1997, pp. 180–181). Indeed, two wings are missing on the ground floor and first floor, which would have given unity to the porticoed courtyard, and the external finish of the complex is incomplete. This incompleteness nevertheless allows to appreciate countless aspects of Biagio Rossetti's architectural language (Bassi, 2005).
The layout of the courtyard of Palazzo Costabili unfolds as a double loggia, arranged in a 2:1 ratio and decorated with stone bands that connect the two levels (Fig. 2). These bands alternate between the columns and the centre of the arch, influencing the overall perception of the courtyard and interacting directly with the architectural composition (Mattei, 2018, p. 44).
Palazzo Costabili has been selected as test-bed to experiment AI-based methods and tools to analyse surface features that, in particular, on the main façade and on the side of the courtyard, are characterised by complexity and stratification and featuring different types of brickwork.
In this framework, the multi-scalarity is assumed as a critical threshold in computational drawing, as it is one of the most significant intrinsic characteristics of manual drawing. The observer is able to simultaneously relate the scale of the individual element (the brick), the configuration of the fabric, the composition of the façade, and the historical context of the project. This scalar continuity is not a sequential process, but an integrated one.
In computational systems, by contrast, analysis takes place across distinct layers: local features, thematic classifications, and separate datasets. The scale is modular, not simultaneous. Integration between different levels requires explicit protocols and correlation architectures designed in advance.
The multi-scalarity thus becomes a central methodological issue: the problem is not the ability to analyse complex data, but the ability to maintain interpretative continuity across scales.
The case study of Palazzo Costabili, due to its architectural relevance, comprises extensive historical documentation, also concerning its construction phases, a necessary condition for a reliable analysis of historical masonry (Cocchi, 2010). This body of knowledge made it possible to establish an initial geometric and metric reading of the masonry textures, considering the dimensional properties of bricks as a preliminary interpretative parameter, allowing the integration of survey data, historical sources, and dimensional parameters within a unified analytical framework, supporting the subsequent phases of discretisation and interpretation.
The analysis focused on the reading of masonry textures through automated segmentation tools, to assess the models' ability to recognise and differentiate the fundamental pattern' morphological features. Attention was therefore directed to recurrent visual and material aspects of the surface, including element arrangement, brick-mortar relationships, and variations in texture, which were used as a basis to test the limits and potential of algorithmic interpretation.

APPLIED METHODOLOGY

Given the specific objective of the analysis, the survey was designed and carried out to generate orthophotos of selected elevations.
The survey methodology involved the use of a Leica P40 laser scanner for the acquisition of a "structural" point cloud, obtained from 24 scan positions registered through common targets (mean error: 2 mm). From this dataset, the coordinates of control points for the detailed photogrammetric model were extracted, materialised through black-and-white targets (Fig. 3). A DJI Mini 4 Pro drone was used for aerial image acquisition, while

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Figure 4. West Elevation of *Cortile d'Onore*, orthomosaic obtained from photogrammetric processing. Graphic elaboration by the authors.

a Canon EOS 90D camera was employed for terrestrial photography (Fig. 4).

The segmentation of the orthophotos was performed using a Deep Learning model (DeepLabV3+), trained on a specifically constructed dataset for the recognition of bricks, mortar joints, and stone elements (Loverdos & Sarhosis, 2022). The model was trained using a supervised approach, based on a dataset of 147 manually annotated images. The photographic sample was acquired by documenting different masonry walls located in the Ferrara historic centre, selected in order to represent various brick typologies and different finishes of mortar joints, particularly in terms of thickness and construction technique.

The surveyed surfaces include both homogeneous masonry systems and more heterogeneous conditions, in which stone elements are integrated within the masonry fabric, to enrich the dataset and calibrate it to the specific characteristics of the Renaissance masonry tradition in Ferrara. All images were then pre-processed through cropping operations, ensuring consistent framing focused on brick texture and on the surface detail of the masonry.

This standardisation was adopted to guarantee dataset uniformity and to improve the consistency of visual patterns used during model training. The inclusion of façades with lithic elements embedded in the masonry was an intentional choice, aimed at increasing sample variability and representing real construction conditions typical of the historical stratification of the urban fabric.

For the annotation process, the Roboflow platform was used, and the annotated image sample was subjected to data augmentation procedures (horizontal flip and contrast adjustment). The dataset was split into training (70%), validation (20%), and test (10%) sets to train the model over 30 epochs. The best-performing model was selected based on the overlap between predictions and ground truth. For the class of interest in this analysis (brick), the validation metrics yielded the following values: Intersection over Union (IoU) = 0.818, Precision = 0.914, Recall = 0.886, and F1-score = 0.900. The model was then applied to the orthophotos to perform segmentation, producing a comprehensive brick mask for each façade (Fig. 5) (Vandenabeele et al., 2024).

The brick mask can serve as the basis for the automatic delineation of brick profiles, on which geometric analyses can be performed. These analyses are useful both to facilitate visual inspection of the results, making bricks with anomalous height and width immediately identifiable, and to highlight areas where two or more bricks have merged vertically or horizontally (Fig. 6).

The vector output serves as a tool for controlling and verifying the results of the algorithmic procedure. Through it, critical issues emerge in the correct identification of thin mortar joints or in areas where the masonry shows traces or residues of limewash or mortar, which make the brick–mortar joint boundary less distinct.

The drawing of the masonry texture allows to identify more reliable areas of the output, where local analyses can be carried out to study brick dimensions and, subsequently, to investigate historical–stratigraphic and conservation aspects. The sample areas selected for this in-depth analysis were selected based on existing literature and previous studies, in order to obtain comparative reference data. The analysed sources (Cocchi, 2010) refer to the external façades overlooking the garden, specifically the south and west elevations, attributed to a construction phase dating to the early sixteenth century. The dimensions of the bricks in the analysed samples (Fig. 7) are consistent with those reported in the literature for buildings in Ferrara from the same period.

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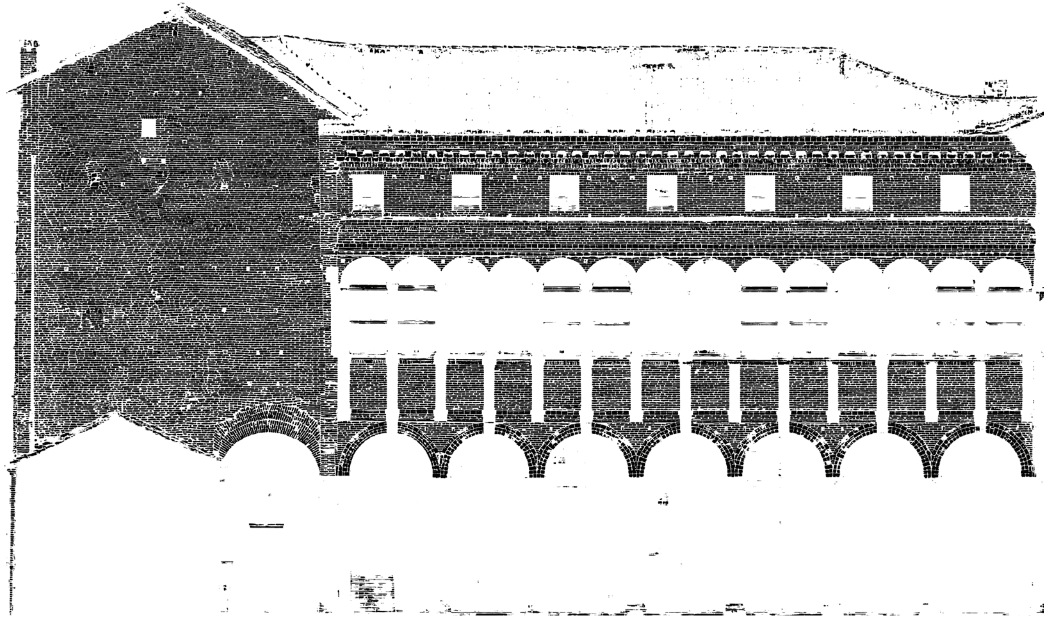

Figure 5. Brick mask of the west elevation of *Cortile d'Onore*, obtained through algorithmic segmentation of the orthomosaic. Elements recognised in the brick class are shown in black. Graphic elaboration by the authors.

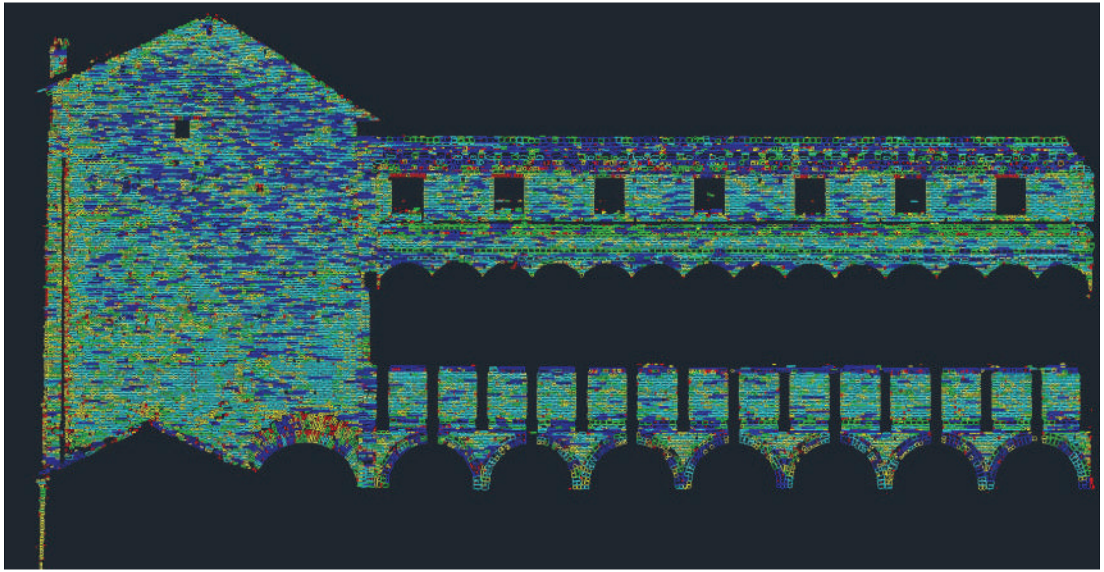

Figure 6. Dimensional analysis of the automatic vectorisation of the brick mask of the west elevation of the *Cortile d'Onore*. The elements were classified into five user-defined categories based on width: less than 8 cm in red (outliers and brick fragments), between 8 and 15 cm in yellow (headers), between 15 and 22 cm in green (three-quarter bricks), between 22 and 32 cm in cyan (stretchers), and greater than 32 cm in blue (elements not referring to a single brick). The blue colour also highlights bricks that have been horizontally merged, thereby identifying areas of lower accuracy in the algorithmic output. Graphic elaboration by the authors.

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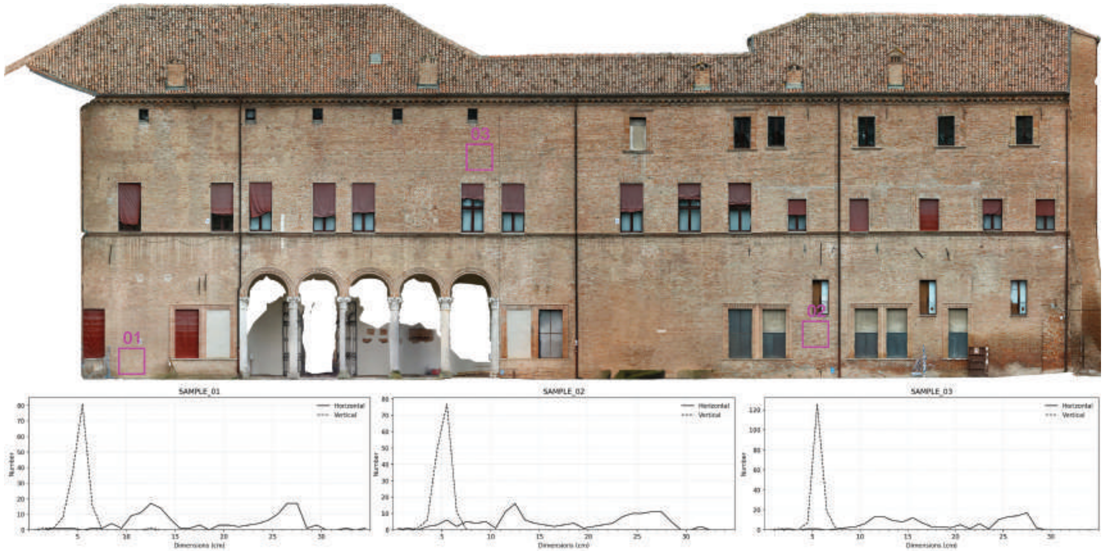
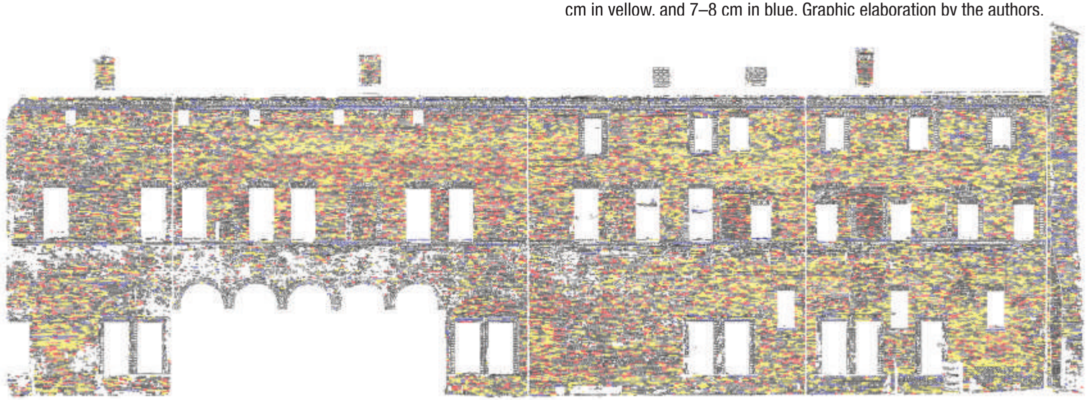


Figure 7. Dimensional analysis of bricks in three areas of the south elevation overlooking the garden. Samples 01 and 02 correspond to those analysed in the literature. Despite the presence of numerous fragmented bricks, which complicate the unambiguous identification of width and length, the most recurrent dimensions can be identified as height between 5 and 6 cm, width between 12 and 13.5 cm, and length between 27 and 28 cm. Graphic elaboration by the authors.

Figure 8. Extensive classification of the elements identified through algorithmic processing of the south elevation, with visualization of the three most recurrent categories according to the literature: 5.3–5.4 cm in red, 5.8–6.1 cm in yellow, and 7–8 cm in blue. Graphic elaboration by the authors.



The bricks used have lengths ranging between 28 and 28.4 cm and widths between 12 and 13.5 cm, with an average thickness of approximately 5.9–6 cm (Di Francesco et al., 2006).The difficulty in assigning recurring values for lengths and widths is confirmed, due to the frequent presence of fragmented elements, whereas the data for heights prove to be more consistent, allowing classification into three recurring dimensional groups: 5.3–5.4 cm, 5.8–6.1 cm, and equal to or greater than 7 cm (Cocchi, 2010).
Based on this observation, it was possible to apply the analysis extensively across the façade, automatically identifying bricks whose heights are included within these three categories and making them explicit through a colour-coded mapping (Fig. 8).
The opportunities arising from this approach open new possibilities for understanding historical architecture, enabling the verification, on a broader scale, of analyses previously developed at a local level. However, this type of analysis is strongly influenced by the reliability of the algorithmic processing output, which, as previously noted, is affected by inaccuracies in the identification of individual bricks. These inaccuracies can be statistically reduced but never completely eliminated. Furthermore, the presence of decorative elements (string courses, cornices) and structural features (lintels, arches) inevitably interrupt the homogeneity brickwork and can only be correctly interpreted based on critical “human” expertise. Additional interference may also derive from elements that partially obscure the underlying masonry (e.g., downpipes). Two strategies can be adopted: either removing anomalous elements after the first verification of the output, thus not fully applying the analysis to the entire façade, or correcting the brick mask (or its vector representation) prior to computing dimensions, thereby increasing manual processing time.
The brick mask obtained directly from the algorithmic processing, even in its “raw” form, can still serve as a valuable support tool for the analysis and interpretation of the masonry. For instance, it can make certain alignments between bricks or

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areas with different masonry patterns more immediately apparent (Fig. 9).

DISCUSSION

In the case study of Palazzo Costabili, the shortcomings of automatic segmentation processes are particularly evident. Although the model was trained on datasets structured from brickwork in the Ferrara area, including different laying patterns and historical stratifications, it fails to recognise certain morphological configurations as organised systems. Elements such as the rhythmic variations in the texture or the sawtooth pattern of the main façade are represented as aggregations of discrete occurrences, lacking hierarchical and structural relationships (Fig. 10).
The issue, therefore, does not concern the ability to recognise individual elements, but their integration into a coherent structure. Automatic segmentation, based on local patterns, tends to isolate components without capturing the relationship between part and whole, highlighting a substantial gap between algorithmic discretisation and architectural interpretation (Valero et al., 2019; Ottoni et al. 2017).
This condition is closely linked to the nature of the models and, in particular, to the structure of the datasets on which they are trained. In the case analysed, the annotation process introduces a preliminary classification distinguishing between bricks, mortar (considered as background) and stone elements, including various types of masonry. This operation is already a form of interpretation of reality: it defines classes, levels of granularity and criteria transferred into the model. In this sense, computational data is never neutral, but the result of an epistemic construction that reflects methodological and cultural choices (Murtiyoso et al., 2022).
It follows that the so-called "objectivity" of the model is always mediated by an interpretative framework: the system learns what has been preselected and organised, but is unable to concept complex relationships autonomously or to integrate different levels of information according to a multi-scale logic. This limitation becomes particularly evident in the field of architectural heritage, where understanding historical surfaces requires a relational and stratigraphic interpretation.
The integration of surface analyses, such as class-based masks or textures, further amplifies the amount of available information, making material and geometric micro-variations visible. However, this increase in information does not automatically translate into greater interpretative capacity: on the contrary, it highlights the discrepancy between

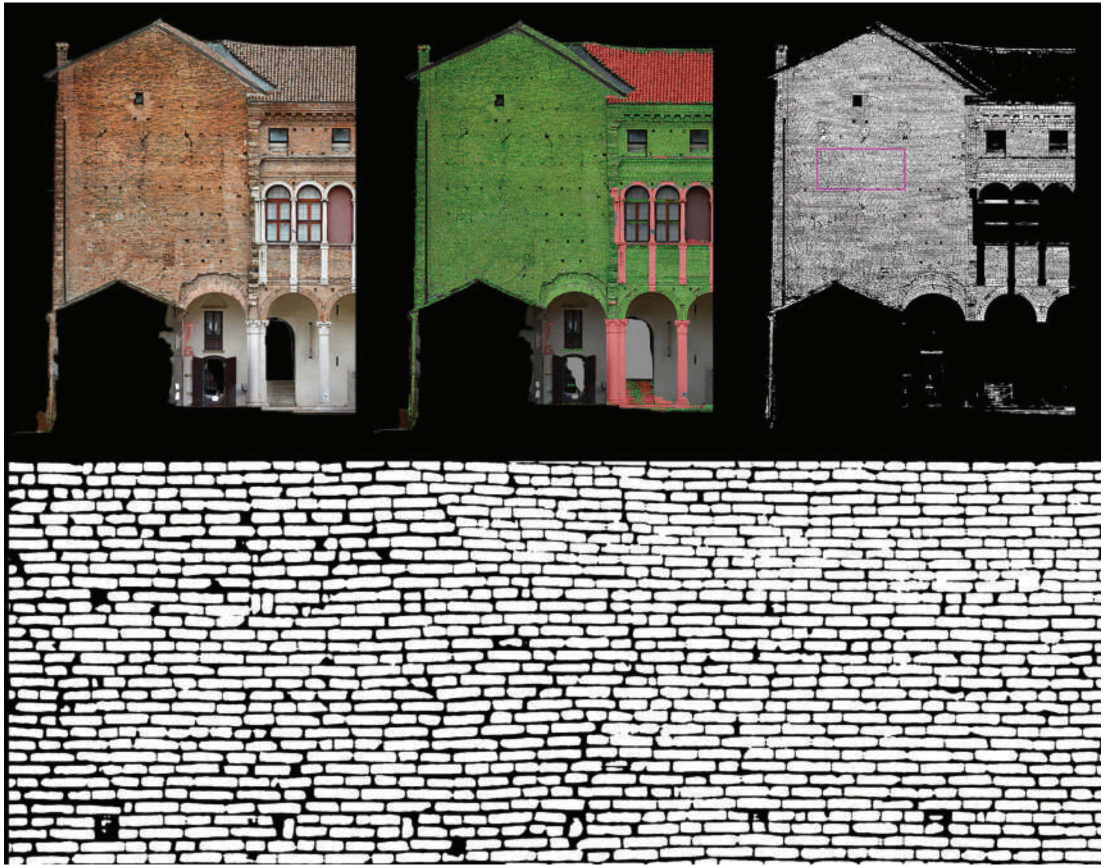

Figure 9. The brick mask obtained from algorithmic processing, if critically interpreted, can support the reading of surface features. In the case of the main façade of the building, on the west elevation facing the *Cortile d'Onore*, a diagonal trace emerges, formed by the alignment of several vertical mortar joints. Starting from the junction between the main façade and the roof, this feature extends continuously for approximately 9.8 m. Graphic elaboration by the authors.

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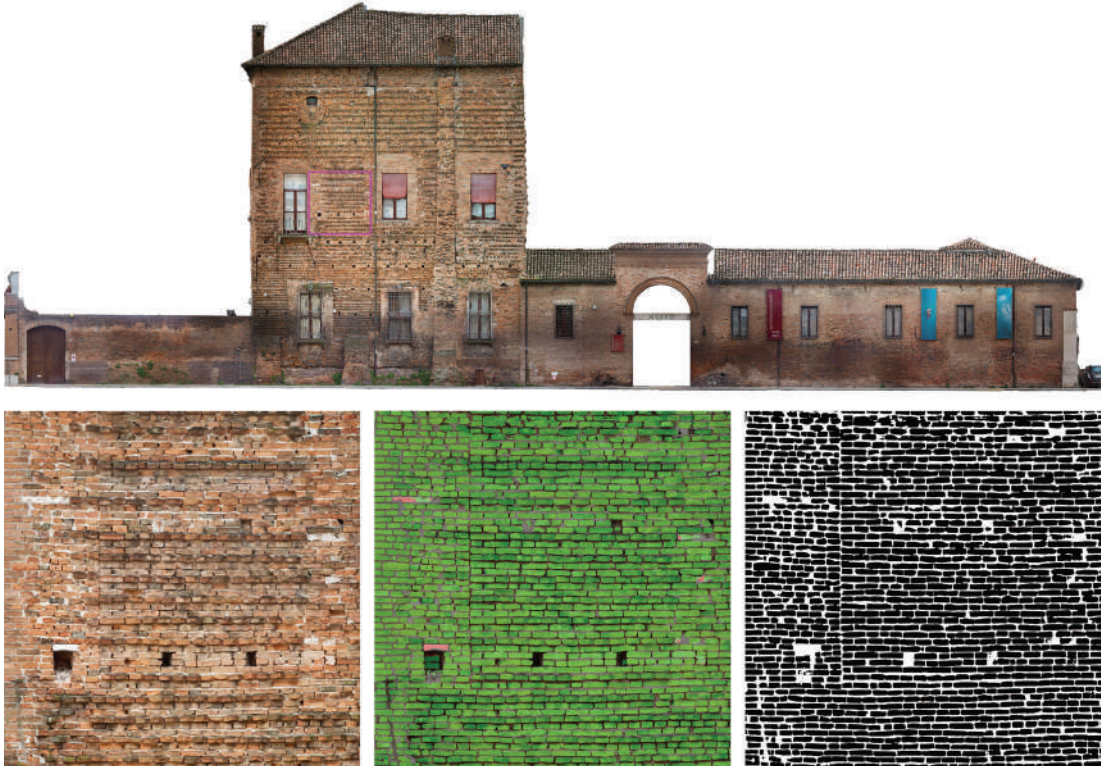

Figure 10. Analysis of a portion of the masonry of the main façade. Morphologically complex elements, such as variations in the plane or sawtooth patterns, are not captured by the automatic segmentation. Graphic elaboration by the authors.

the physical continuity of the architecture and the algorithmic fragmentation of the representation.
Added to this is the issue of scale. In computational systems, analysis is organised into distinct levels (feature extraction, classification, semantic mapping) whose coherence must be explicitly designed. In manual representation processes, however, the relationship between detail and the whole is intrinsically continuous, allowing for a simultaneous and integrated reading of the architectural system. The loss of this continuity represents one of the main limitations of segmentation models.
A further critical issue concerns the reliability of the results. Evaluation metrics (IoU, precision, recall, F1-score) are based on comparison with an annotated ground truth, which is itself a partial and simplified representation of reality. The finite nature of the dataset, the presence of unforeseen elements in the application images, and the possible presence of annotation errors introduce a discrepancy between statistical validation and interpretative validity.
In this context, there is a need for epistemic oversight capable of ruling the entire process. Interpretation is not eliminated by AI systems, but shifts upstream: into the dataset design, the definition of classes, and the structuring of training pipelines. Without interpretative guidance, algorithmic output tends to remain on a quantitative level, producing consistent classifications (always with a certain degree of accuracy) but not necessarily meaningful ones.
Within this hybrid scenario, drawing assumes a central and renewed role. It is not limited to the final output, but acts as a critical device for mediation and validation, capable of reintegrating hierarchical relationships, scalar continuities and stratifications that segmentation tends to fragment. Drawing thus becomes the interface through which segmented data is reorganised into an interpretative structure (Maietti, 2023).
This leads to a crucial distinction. The AI systems tested produce a discretisation based on local classifications, without a relational syntax; drawing, by contrast, develops a language capable of organising data into a coherent system of relationships and meanings. The difference lies not in the ability to recognise reality, but in the ability to construct an interpretative form of it.
From this perspective, the Costabili case confirms that automatic segmentation, whilst representing an advanced tool for the analysis of the built environment, is unable to replace the interpretative reading of architecture. Only through critical mediation, in which drawing plays a central role, can data be transformed from discrete information into structured architectural knowledge.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The experiments show that, despite good performance in the classification of individual elements, segmentation is unable to reconstruct complex configurations as organised systems, instead fragmenting architectural patterns and losing the relationships embedded in the hierarchical and multi-scalar syntax of architecture. This limitation

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is related both to the nature of the models, which are based on local patterns, and to the structure of the dataset, as well as the implicit interpretative choices embedded in the annotation process.
The results further indicate that, in the absence of interpretative guidance, algorithmic output tends to remain predominantly quantitative: although automatic recognition can produce coherent classifications, these are not necessarily organised according to a critically meaningful structure. From a statistical perspective, the reliability of AI-based processes is commonly expressed through metrics such as accuracy and precision, computed on a test set by comparing predicted outputs with manually annotated ground truth. However, these indicators only partially describe model behaviour under real-world conditions and are not sufficient to ensure full reliability in terms of architectural meaning (Brusaporci, 2023).
Within this framework, a structural distinction emerges between computational data and architectural descriptors. AI produces information of a static and quantitative nature, extensive and measurable through interpolations of metric-geometric data over potentially non-selective analytical ranges. In such conditions, it is the operator who must guide the process, defining interpretative criteria and structuring information according to analytical objectives. So, the extensiveness of the output may include ambiguous or geometrically non-unique configurations, which require further systematisation in order to become reliable data. These outputs thus remain analytical representations not yet organised into a critical form.
By contrast, survey consists in constructing synthetic descriptors of the interpreted reality: representation, both in 2D and 3D, necessarily involves processes of selection, hierarchisation, and systematisation of information aimed at producing a structure that is both legible and verifiable with respect to the real world (Fiorani & Acierno, 2017). In this sense, AI does not replace interpretation but rather reconfigures its scope. The epistemic act shifts from the result to the process: from the definition of the workflow and protocol to dataset construction and outputs critical supervision. Drawing is therefore not superseded by automation but redefined as a device for control and mediation, capable of reintegrating spatial relations and hierarchies that segmentation tends to dissolve.
From this perspective, drawing is not merely a representational tool but a cognitive infrastructure that enables the governance of computational processes and the recomposition of interpretative complexity dispersed through algorithmic discretisation. The issue is not a dichotomy between human and machine, but the construction of an integrated system in which interpretative responsibility remains central, and in which segmented data can be transformed, through critical control of drawing, into structured and validated architectural knowledge.

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AUTHORS CONTRIBUTION

Although the paper was written in close collaboration between the authors, the authorship of the paragraphs is as follows: F.M. is the author of paragraphs "Introduction", "Renaissance wall textures as a test-bed", and "Discussion"; G.G. is author of paragraphs "Applied methodology", "Discretisation as an epistemic act", and "Discussion". M.S. is the author of paragraphs "Discretisation as an epistemic act", "Applied methodology", and "Discussion". Paragraph "Conclusions and future developments" was written jointly.

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