THE MENSIOCHRONOLOGY ANALYSIS SUPPORTED BY NEW ADVANCED SURVEY TECHNIQUES: FIELD TESTS IN MILANESE AREA

L. Cantini *, M. Previtali, R. Moioli, S. Della Torre

Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering,
Via Ponzio 31, 20133 Milano, Italy - (lorenzo.cantini, mattia.previtali, rossella.moioli, stefano.dellatorre)@polimi.it

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ABSTRACT:

Mensiochronology of brickwork, even in areas where reference curves have been constructed and well tested, requires precise measurements and a representative amount of data due to the many factors affecting the reliability of the measurements, such as the defects caused by the time and the environment that changed the geometry of the bricks (deformation or lack of material along the edges), as well as the operators' skills. Sometimes, the number of measurable bricks is limited in a wall, or in a stratigraphic unit. Furthermore, if a scaffolding is not available, the analysis is concentrated only on the lower courses of the bricks, being not possible to directly measure the bricks of the higher levels. In order to implement the number of bricks taken into account for this study, a comparison from direct measurements and indirect measurements is here proposed.
The aim of this paper is to explore the applications of photogrammetry for undertaking brick measurements for chronological dating: its advantage and drawbacks. Using high-resolution digital rectified pictures, the masonry texture of some well-documented building prospects was scaled into vector graphic software for recording the measures of the bricks. The results presented here by the authors are an attempt for validating this method for future applications. In detail, three case studies are analysed in the historic centre of Vimercate (Italy) testing the effectiveness of the presented method on dated buildings that display diverse features, including the presence of reused bricks, possibly coming from dismantled pre-existing structures. The results proved that the proposed geomatics method entails an accuracy that does not affect the usability of data for the investigation of buildings and the material culture inbuilt.

1. INTRODUCTION

Mensiochronology is an investigation method for the analysis of buildings through the chronological dating of brickwork based on the dimensions of the elements. The method is based on assumptions concerning the whole material culture that created the examined building (Musso, 2015): therefore, it can lead to various observations on the construction history, going beyond the issue of the date. The data provided by mensiochronology have to be cross checked with information made available by indirect sources (archival and bibliographical) and with other observations. As the technique is based on the study of regional markets, a wide investigations of case studies and local production conditions is required. It was developed mainly by the school of archaeology of architecture in Genoa (Mannoni, Milanese, 1988; Mannoni, Boato, 2002; Pittaluga, 2009), then it was replicated in other cities. Studies on mensiochronology in Lombardy have been carried out as well (Casolo Ginelli 1998; Gaggioli 2012). The present study has been developed in the frame of a series of studies, parallel to didactic activities, in Vimercate, a small historic town nearby Milan that offers both the case studies and the realm, in which studies get some involvement by the local community (Della Torre, Moioli, Cantini, 2019). The most common building technique in this area used to mix pebbles and bricks arranged in the form of "opus listatum" (Della Torre, Cantini, Moioli 2018). The distance from Milan is approximately 20 kilometres, but at less than 10 kilometres it is possible to reach the Naviglio della Martesana canal, a historical water way connecting Milan to its north-east countryside, which could be used for the transportation of building materials. As observed in various researches on the main buildings characterizing Vimercate town centre and their owners, patrons and engineers came from Milan as well, so it is not surprising that building practices tended to follow the trends of the capital of the Duchy.

2. MENSIOCHRONOLOGY AND OPERATIVE ISSUES

Acacia et al. (2017) proved the feasibility of using photogrammetric techniques to undertake measurements of bricks for chronological dating. One of the main advantages of photogrammetry is the decrease of time requested for the on-site survey. Indeed, in a few minutes it is possible to acquire the primary data that can be used to create a digital model suitable to be used later for brick measurements.
The present study aimed at extending the discussion on the use of photogrammetry for mensiochonological studies, taking into account the feasibility of the investigation extended to brickwork facades not directly accessible, for which rectified images will be the only basis for measurements.
The study therefore has a twofold purpose: on one hand it investigates an area, in which the use of bricks was certainly relevant and continuous in building practices; on the other hand, it wants to test if the analyses carried out on the basis of rectified images provide reliable information.
For this purpose, a sample of buildings have been selected, on which indirect information is detailed enough to formulate hypotheses that will enable to check data provided by mensiochronology. In a couple of cases the masonry presents only bricks in the facades, while in the others the wall is made of pebbles and bricks: this means that the number of identifiable

* Corresponding author

bricks in each stratigraphic unit (USM) is limited and only the thickness will be representative for a statistic treatment.

Different authors suggested different levels of accuracy of the measurements carried out for this dating technique. Even more than for other techniques, this one is sensitive to several factors that affect the accuracy of the measurements: the state of conservation of the bricks and their own non regular shape, the attention paid by the operators, the type of pointing, and so on. The statistic treatment tends to compensate errors, as they are not systematic.

The experiences carried out in Milan used an accuracy of 1 mm, and the same has been adopted for the present study. The label value represents the thickness characterizing the bricks, which are present in a stratigraphic unit, is meaningful, but should always be interpreted: the reference curve proposed for Milanese area (Casolo Ginelli 1998) has been identified as a linear regression of a set of data observed in a number of buildings bearing reliable dates, with values that vary in a confidence interval (Figure 1). Therefore, the meaning of label values should always be supported by a qualitative assessment as well and accuracy could be just one of the factors on which mensiochronology plays.

3. THE SAMPLE

The considered buildings present stratified constructive units, testifying the transformations occurred in various periods. In detail, the mediaeval St. Antonio Oratory offered two elements realized along the 17th century in brick masonry: the small bell tower and the apse, both documented in archive documents. The palace of the feudatory of the town, Secco Borella and later Trotti family, is documented since the beginning of the 17th century and presents a mixed masonry composed by pebbles and brick courses. During the end of the same century, the bell tower of the main church of the town was realized in brickwork. These three cases, with their specific stratigraphic units, allowed carrying out direct and indirect measurements on different areas. The analysed stratigraphic unities cover a time spanning long enough from the beginning to the end of the 17th century.

Studies on mensiochronology in the Milan area had been carried out in the 1990s (Figure 1), identifying an area limited to the centre of Milan and the villages along the canals (Casolo Ginelli 1998). A wider diffusion of the market rules observed in this area is a hypothesis, which has to be proved. The first tests suggested the existence of a tendency of the brick thickness to diminish, maybe following the same rules observed in Milan city area (Della Torre, Cantini, Moioli 2018).

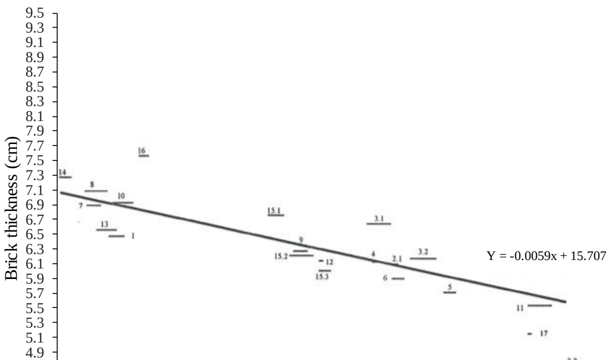

Figure 1. The mensiochronologic curve of the city of Milan and its surroundings (Casolo Ginelli 1998: 57)

The sample has been selected on the basis of available precise dates given by indirect methods, and also because they offer significant historic questions for applied mensiochronology. Furthermore, they offer the conditions to test photogrammetric issues.

Although a small building, S. Antonio's church (Figure 2) in Vimercate features several construction phases, whose technologies can be easily observed on the external walls that are not plastered. Its origin is uncertain (Bairati 1994), the first two building phases encompassing the unique nave. Unpublished archival documents enable to give an undisputable date (after 1574) to the internal pointed arches supporting the roof, and the contemporary raising of the lateral walls (Figure 3). The original semi-circular apse was substituted by a wider square choir in 1615-1625, enriched by a classical triumphal arch, expressing the will and the taste of the bishop Federico Borromeo.

Figure 2. St. Antonio Oratory: a) the façade; b) the bell tower and c) the rectified north side with its stratifications.

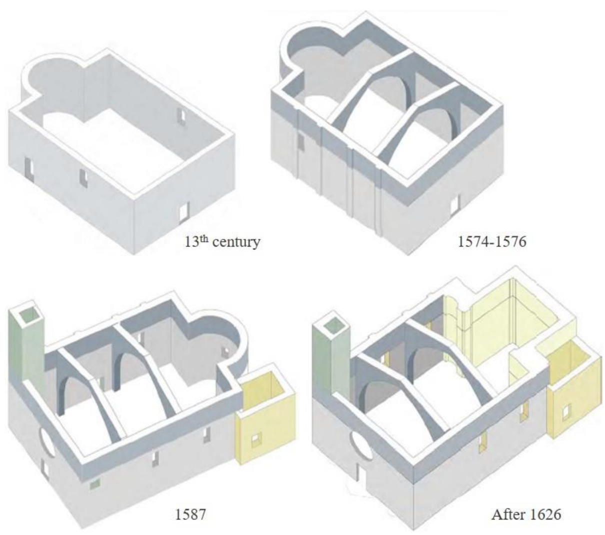

Figure 3. St. Antonio Oratory main evolution phases layouts.

S. Antonio's bell-tower is a special topic of this analysis. A small tower had been built between 1590 and 1615 in the same position of the existing on, that is in the northern corner of the façade, but the date 1673 legible on the bells suggested to previous authors that in the same year the bell tower itself was built. The problem is therefore open, and the bricks measures could support one of the hypotheses. The bell tower enables both to identify a good sample testing photogrammetric methods and a small sample of bricks at the internal base, which can be measured directly.
As for the other bell tower of Holy Virgin Sanctuary (fig. 4), specific documents on its building history have been found in the Plebano Archive in Vimercate (Sannazzaro 1995: 178-179). The works were directed by the engineer Francesco Bianchi from Milan, who is deemed to be also the author of the project and lasted from 1688 to 1694. The external facades are accessible from the public street, so in this case it is possible to carry out direct measurements and to shoot photos. The sample represents also an optimal choice to be placed on the Time axis.

Figure 4. The Sanctuary of the Holy Virgin of the Rosary: a) the bell-tower; b) a sky view of the church and c) its masonry.

Trotti palace was built in the last years of 17th c. to widen and update the former residence of the family Secco Borella counts of Vimercate, dating back to 15th century (Ferruzzi 1990). The project was never finished, but a large two storey building was completed, with central main halls flanked on the East and West edges by apartments, each composed by three rooms: a private hall with a fireplace, the anteroom and the bedroom ("alcova").
The construction started from the East side, where the pre-existing canteen was extended, proceeding westwards by additions of entire blocks from the ground to the roof, corresponding to the internal partitions (Figure 5). The process can be clearly detected by means of the stratigraphic relationships, which are visible in the façade on the courtyard (Figure 6a), where the foreseen porch with twin columns has never been built (Figure 6b), nor the walls have been plastered (Figure 6c). The position of the tie rods helps in the reconstruction of the building process. A first certain chronological term is given by the date 1705, which legible in the frescoes of Cleopatra's stories in the main hall at the ground floor.
During the construction of the new building, the old one was progressively dismantled, leaving the minor wings of the internal courtyard. More than the detailed story of the Palace, not perfectly enlightened by the few archival documents, what matters here is that also on the yard recyclable materials were available. Therefore, an interesting problem arises for the mensiochronology, as it is likely that in the walls both bricks produced at the time of the works, and recycled bricks are to be found, the latter having the dimensions typical of the demolished old buildings. The histograms are expected to feature asymmetrical distributions, and this is the reason why this sample has been considered to complete the significance of this research. As an example, the graph reported in figure 7 shows the large range of different dimensions directly measured on the walls of Trotti Palace, due to the use of new (corresponding to 50mm thickness) and retrieved bricks.

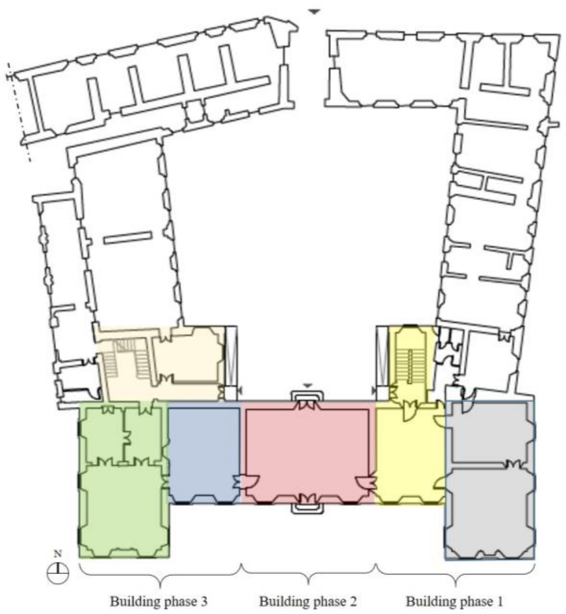

Figure 5. Plan of Trotti Palace complex with a layout of the main constructive phases of the principal 17th century building.

Figure 6. Trotti Palace: a) main courtyard with the incomplete side; b) the representation of the courtyard in a fresco at the ground floor and c) detail of a connection for the cloister.

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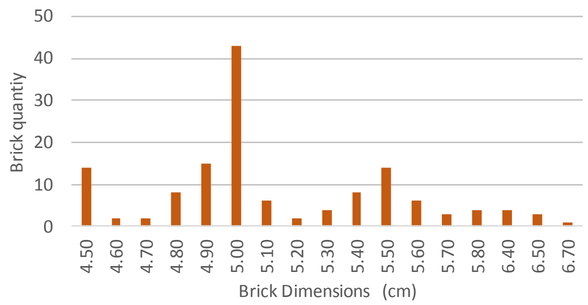

Figure 7. Example of the brick dimensions (thickness) distribution obtained by direct measurements carried out at the base of Trotti Palace courtyard walls.

4. THE RECTIFICATION TECHNIQUE

In Acacia et al. (2017) is discussed the feasibility of using photogrammetric techniques to undertake measurements of bricks for chronological dating. One of the main advantages of photogrammetry is the decrease of time requested for the on-site survey. Indeed, in a few minutes it is possible to acquire the primary data that can be used to create a digital model suitable to be used for brick measurements later on. A second main advantage of photogrammetric techniques is the possibility to measure in a reliable way also objects that are located far from the operator and would need, in the case a manual measurement, some specific support (e.g., ladder, scaffolding, etc.). One of the main aspects to be taken into account when planning the survey is the level of details that is required for the mensiochronology analysis. This may be a critical aspect in the case the object to be surveyed is far from available acquisition standpoints (like in the case of the Sant' Antonio bell-tower presented in Section 5). Indeed, in this case a telephoto lens may be required to achieve a Ground Sampling Distance (GSD) allowing an accurate measurement of the brickwork and more specifically for every single brick. For this specific purpose GSD cannot be larger than 1.0 – 2.0 mm. On the other hand, by using long focal length cameras may result more difficult (Stamatopoulos and Fraser, 2011) to acquire images with a good network geometry (with an adequate baseline). This may end up with some problems in image alignment and/or dense matching steps resulting in an inaccurate geometry reconstruction. However, in many cases the mensiochronology analysis has to be performed on brickworks that can be assimilated to planar elements like walls. In those cases, a simpler image rectification may be carried out and solve the problem connected with the network geometry. However, due to the limited field of-view (that can be smaller than 10°) the number of images to be rectified may increase in a significant way if we want to analyse a wide area. This turns out in a cumbersome and labour-intensive manual operation. In addition, a significantly larger number of Ground Control Points (GCPs) has to be surveyed with other instruments (e.g., total station) to carry out the rectification of each image separately. To partially overcome the previously listed limitations, in this paper we are presenting a solution based on the stitching of single images in order to derive a unique gnomonic projection that can be rectified. Advantages of the presented methods are:

1. Objects far from available acquisition standpoints can be surveyed without paying specific attention to network geometry since a single standpoint is used reducing in this way the requested time for on-field image acquisition.
2. Obtained gnomonic projection presents the same level of detail GSD of the original images but with a larger field-of-view.
3. Reduction of the number of GCP needed for image rectification since a unique gnomonic projection image is used instead of a large number of narrow fov images.

To generate the gnomonic projection, we have to take into consideration that a set of images taken with a rotating camera. A rotating camera is a standard central perspective sensor that can rotate only around its perspective centre so that different images acquired with this camera have the same perspective centre but different attitude.

To create such a rotating camera, we developed an ad-hoc mechanical rotating head that consisted of a cardan joint that allows the camera to rotate around it (Figure 8). The Rotating head needs to be calibrated in order to find the perspective centre for a generic lens mounted on the camera (Barazzetti et al., 2013). Images acquired with a rotating camera can be registered and stitched through homography. The transformation between two images i and j can be expressed as follows (Hartley and Zisserman, 2004):

$$X_i = H_{ij}\, X_j = K\, R_i\, R_j^T\, K^{-1}\, X_j \tag{1}$$

where X_i and X_j are vectors of homogenous image coordinates, H_{ij} is a transformation matrix, K is camera calibration matrix, R_i, R_j are the rotation matrices of both images. This equation can be extended for a generic set of images gathered with the rotating camera.

Figure 8. The cardan joint based rotating camera system.

The co-registration of all images acquired with the rotating camera (i.e., estimation of the transformation matrix H_{ij}) can be performed extracting of a set of corresponding tie points from overlapping images. In the presented work the estimation of tie points was carried out in an automated way using the scale-invariant feature transform (SIFT) algorithm (Lowe, 2004). The matched image points allow the estimation of the unknown parameters within a bundle adjustment. Once images are co-registered they are mapped into a high high-resolution mosaic with a gnomonic projection (Figure 9). The obtained mosaicked image follows the standard pinhole camera model (Barazzetti et al., 2014). It is worth to mention that gnomonic projection can be used up to a field-of-view of about 40°-50°. For larger field-of-view the gnomonic projection will give strong deformations. In the case of the Sant' Antonio bell-tower the average error on the tie point is less than 1 pixel demonstrating the feasibility of the rotating head to reproduce a rotating camera.

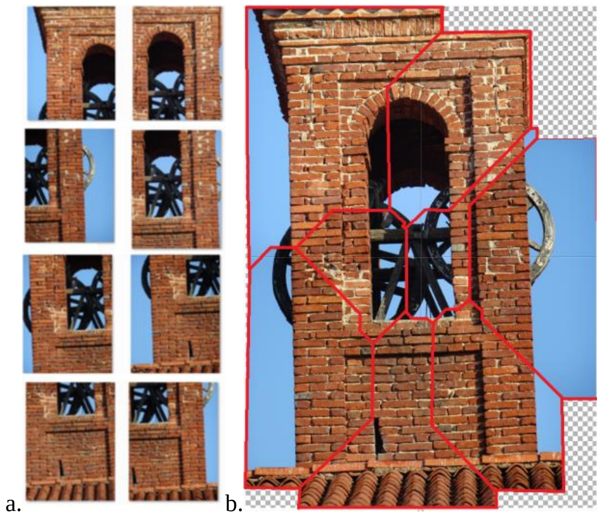

Figure 9. Stitching of the images to generate a gnomonic projection: (a) the original picture; and (b) the gnomonic projection obtained as a mosaic.

Control points on the bell tower (the main plane of the bell-tower was used as a reference) were measured by using the total station Leica TPS 1200. The accuracy of each point measurement is ± 2.0 mm. Figure 10 presents the planimetric (x, y) distribution of the GCP. The control points were rotated (using least squares line fitting) so that the X axis is parallel to the bell tower façade.
Rectification of the images is performed using a projective transformation model. The parameters of the transformation are estimated using least squares.
The obtained records contain errors normally distributed in the range of ± 2.0 mm. Therefore, they do not affect the statistic treatment of mensiochronological measures if the samples are composed by a sufficient number of units.

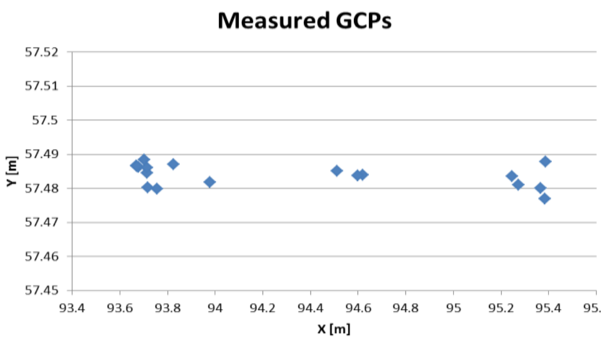

Figure 10. Example of measured GCP for the bell tower.

5. DISCUSSION OF THE RESULTS

S. Antonio bell-tower allowed direct measuring at the entrance, whilst indirect dimensions were obtained from the digital rectifications of the south side of the cell. Two samples have been compared (see Table 1). Sample SAB1 is located at the basis of the tower in one of the new built walls. The thickness of twenty-one bricks has been measured directly, obtaining a very dense distribution around a modal value of mm 60, the average being 60.43 mm and the standard deviation σ = 1,66 In the sample SAB2 located in the higher façade 79 bricks have been considered on the reference plane, obtaining an average of mm 59.99, the distribution being a bit looser (σ = 2,07). The difference among the two average values is therefore minor than the confidence of the rectification, keeping inside the range that is typical of this kind of measures.

	S. Antonio bell-tower	
	SAB1 (D)	SAB2 (I)
Number of bricks	21	79
Average thickness	60.43mm	59.99mm
Modal Value	60.00mm	59.00mm
Standard Deviation	1.66mm	2.07mm

Table 1. Data evaluation from the Oratory bell-tower.

Considering the Holy Virgin Sanctuary, direct measurements were collected at the base of the east and the south sides (HVS1), whilst indirect measurements were carried out on the same area, for comparing the reliability of the method, and on a high level, from 7.50m (HVS2), as illustrated in Figure 11. The average of the thicknesses for a sample composed by 68 measured bricks is mm 59,68, with a very low standard deviation (σ = 2,19), as it was expected on the basis of the documented building procedures.
The same analysis carried out on a rectified area located at 7.5m showed similar values, as reported in Table 2. As for the previous case, the two areas belonging to the same sample can be compared through information achieved by direct and indirect survey, with a difference that is of the same order of the rectification process. Figure 12 presents the comparison between direct and indirect measurements recorded at the base of the east side.

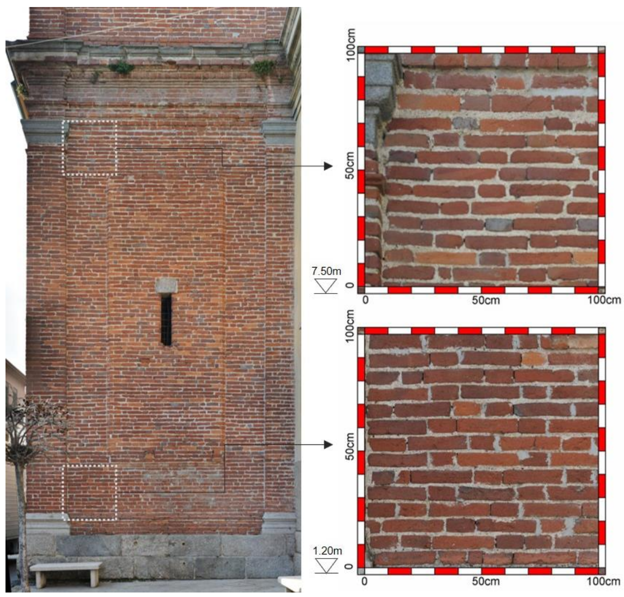

Figure 11. Rectified picture of the east side of the Sanctuary bell tower with two considered areas used for the direct (at 1.20m) and indirect (at 7.50m) measurements.

	Sanctuary bell-tower	
	HVS1 (D)	HVS2 (I)
Number of bricks	68	63
Average thickness	59.68mm	58.44mm
Modal Value	60mm	60mm
Standard Deviation	2.19mm	2.61mm

Table 2. Data evaluation from the Sanctuary bell-tower.

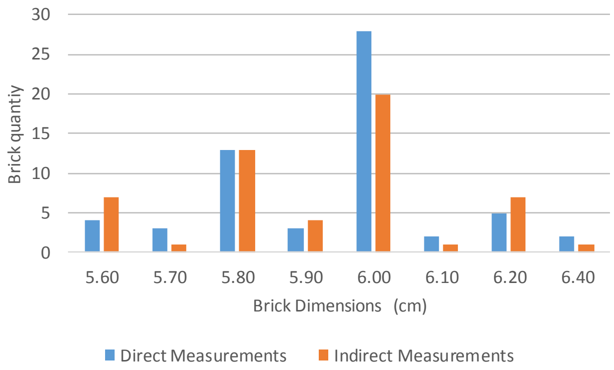

Figure 12. Comparison between direct and indirect measurements carried out on the same area of the bell-tower

In Palazzo Trotti, two sample areas have been chosen on the basis of the stratigraphic analysis. The most significant areas are in the central wing. For each USM an area accessible to direct measurement (1D, 2D) has been compared with a corresponding area of the same USM where indirect measures have been taken on the basis of rectified images (1I, 2I), as shown in Figure 13. The masonry is made of bricks and pebbles, so the number of bricks per sample is not very high, but the obtained distributions are significant.

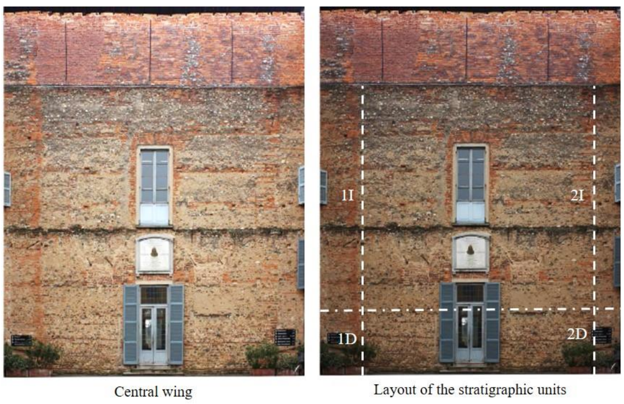

Figure 13. Localization of sampling areas in Palazzo Trotti, Courtyard façade, according to USM (1 and 2) and Direct (D) and Indirect (I) measurements.

The first remark on sample 1D is that the distribution is fairly regular and dense, with only one element definitely thicker than the other ones, obviously recycled and therefore removed from the considered population. The obtained average is mm 50.8, with a modal value of 50 and a standard deviation σ = 2.39. Those values are consistent with what has been observed in some USMs in the East wing, not included in this discussion.
Sample 1I allowed measuring 49 bricks, with an average value of 50.2 mm, with a standard deviation of σ = 4,7 (see Table 3).
Passing on the USM2 recognized in the central part of the building, a very loose distribution can be observed, with an average value of mm 54.36 and a standard deviation σ = 9.22. The higher value of σ means that the percentage of recycled elements becomes here important indeed.
In the upper part of USM2, which is area identified as sample 2I, the indirect measures reveal again a significant modal value near to 50 mm (see Table 4), but the very widespread distribution (Figure 14) includes a lot of thicker elements, signalling that in this building phase more old bricks were used than in the previous phase.

	Trotti Palace USM1	
	1D	1I
Number of bricks	25	50
Average thickness	51.36mm	51.60mm
Modal Value	50.00mm	50.00mm
Standard Deviation	3.45mm	5.65mm

Table 3. Data evaluation from the USM1 of Trotti Palace.

	Trotti Palace USM2	
	2D	2I
Number of bricks	25	60
Average thickness	52.72mm	55.79mm
Modal Value	55.00mm	50.00mm
Standard Deviation	9.22mm	9.04mm

Table 4. Data evaluation from the USM2 of Trotti Palace.

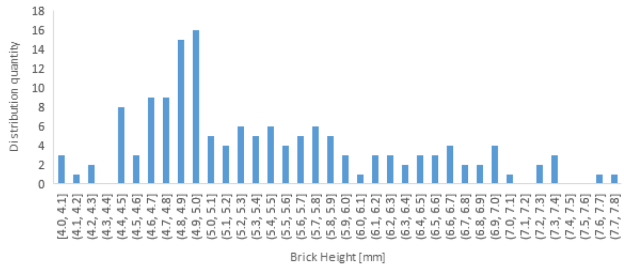

Figure 14. Histogram of the thicknesses in the area 2Indirect

6. CONCLUSIONS

The obtained results comply with the expectations in terms of effectiveness of mensiochronology as an investigation technique.
As for dates, the results are consistent with the reference curve proposed for Milan (Casolo Ginelli, 1998), endorsing the thesis that the relationships with the Milan building sector (same patrons, same architects…) were able to entail the adoption of the same trends in the dimensions of the bricks, even where the transportation of building materials could produce some practical barriers to the oneness of the market.
The dating technique enabled also to solve the uncertainty concerning the bell-tower of S. Antonio’s church, pointing out 1673 as more probable.
As said above, beyond the potentialities for the dating problems mensiochronology encompasses the emergence of several other hints, which can enlighten the general realms of the analysed building yards.
In the sample considered in this paper, the differences that have been detected in the stratigraphic units of Palazzo Trotti are undoubtedly meaningful.
A first issue emerges by the comparison with the bell-tower of the Sanctuary. The difference in thickness seems too big to be explained only by the different dates, which are undisputed. More likely, the control on the quality of the deliveries was tighter for the accurate brickwork of the bell-tower, and looser for the bricks destined to the mixed masonry typology of the palace. In other words, the difference is not a chronological one, but it is a proof of a different quality of the building process.
Even more curious, the presence of recycled bricks: this is an interesting indicator for a building that was born as an addition

and transformation of a pre-existing one. The availability of the old materials seems to change during the building process, as if the demolitions happened after the completion of the first apartments. Thus, mensiochronology does help the investigation of the material culture and the related practices.

As for the question whether the proposed method for indirect measurements can produce results with an accuracy fit for the purpose, or results affected by systematic errors, the designed test allowed comparing direct and indirect analyses in areas belonging to the same stratigraphic units. In all the considered cases, the differences between the samples are minor than the accuracy of the rectified pictures, which enable to include in the analyses samples otherwise not accessible. Therefore, it is possible to conclude that the error induced in the mensiochronological technique presents the same order of the one implied by the adopted geomatics technique, and a trade-off between the accuracy and the meaningfulness of the extended dataset can be evaluated by the researchers.

The quality of the results (see table 5) is the ultimate confirm: the dimensions of the bricks, however obtained, tell the stories of the construction site, enhancing the knowledge of the objects.

Sample name	Sup. date	Meas. type	Bricks (n.)	Mean. thick. (mm)	Modal value (mm)	St. dev. (mm)
St.Antonio bell-tow.1	1673	Dir.	21	60,43	60	1.66
St.Antonio bell-tow.2	1673	Ind.	68	59.99	59	2.07
Sanctuary bell-tow.1	1687	Dir.	68	59.68	60	2.19
Sanctuary bell-tow.2	1687	Ind.	63	58.44	60	2.61
Trotti Palace 1D	17^{th}c	Dir.	25	51.36	50	3.45
Trotti Palace 1I	17^{th}c	Ind.	50	51.60	50	5.65
Trotti Palace 2D	17^{th}c	Dir.	25	52.72	55	7.86
Trotti Palace 2I	17^{th}c	Ind.	60	55.79	50	9.04

Table 5. Comparison among the data collected by the mensiochronology analyses carried out on the considered sample, with the indication of the supposed dating of the units, direct and indirect measurements, the number of the bricks, the average thickness, the modal and the standard deviation values.

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