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Measurement campaign on the historical metallic construction tools and metallic elements of the Brunelleschi's Dome in Florence

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ABSTRACT
This paper presents the results of a measurement campaign aimed at the elemental characterisation of various metallic tools used in the construction of the Dome of Santa Maria del Fiore Cathedral in Florence, as well as several metallic elements inside the Dome. The analysed construction tools, part of the Opera di Santa Maria del Fiore collection, are currently exhibited at the Museo dell'Opera del Duomo, and include turnbuckles, pulleys, three-legged lewises, and pincers. Despite their historical significance, this study is the first to investigate their alloy composition. The metallic elements part of the Dome include both metallic joints used in the chestnut chain and metallic rods on the second and third floors of the Dome. Understanding the chemical composition of the materials used during the construction of the Dome provides valuable insights to deepen our knowledge of Renaissance-era production techniques and the complex history of Brunelleschi's masterpiece. To achieve this, X-Ray Fluorescence (XRF) analysis was employed to determine the elemental composition of the artefacts. Data were processed by chemometric techniques, specifically Principal Component Analysis (PCA), to identify patterns among different alloys. These findings contribute to the historical knowledge of these tools and the Dome itself.

Section: RESEARCH PAPER

Keywords: X-ray fluorescence spectroscopy; principal component analysis; non-invasive measurements; iron-alloys; chemometrics

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1. INTRODUCTION

Part of the monumental complex of the Santa Maria del Fiore Cathedral in Florence, namely Brunelleschi's Dome, is regarded as an architectural masterpiece [1]. At the time of its construction (in the 15^{th} century), it was the largest dome in the world and it still remains the largest masonry dome ever built [2], [3]. Ingeniously erected without scaffolding, the Dome dominates the Florence skyline, measuring 45.5 m in diameter and 116 m in height. Brunelleschi employed a revolutionary self-supporting double-shell technique, constructing two nested domes, one inside the other, linked by twenty-four pillars reinforced with horizontal stiffening arches. The lower portion was built with stone until the curvature allowed for the transition to bricks. However, instead of following the conventional parallel concentric arrangement, the bricks were laid using an interlocking "herringbone" pattern. This innovative approach, coupled with the Dome's distinctive egg-shaped curvature, ensured stability and was the result of meticulous mathematical and geometric calculations [4]–[7].

A narrow stairway of 463 steps winds its way to the base of the tholobate, where visitors can admire the breathtaking frescoes of the Last Judgment, a masterpiece initiated by Giorgio Vasari and later completed by Federico Zuccari. In designing the construction of the Dome, Brunelleschi's genius surpassed both the architectural knowledge of his time and that of ancient Rome, giving rise to the first modern construction site. He not only envisioned the architectural structure but also designed the tools necessary to build it, meticulously overseeing every aspect of the workers' tasks [8]. Filippo Brunelleschi designed extraordinary machines for transporting and installing materials, innovations that later inspired renowned Renaissance architects such as Francesco di Giorgio Martini, Giuliano da Sangallo, Verrocchio, and Leonardo da Vinci. His inventions included large rotating cranes, horizontal and vertical trolleys, levers, and winches with adjustable speeds, all powered by animal strength through a sophisticated system of gears, weights, and counterweights [9]. The Opera del Duomo di Santa Maria del Fiore still preserves in the Museum of the Opera del Duomo in Florence many original tools from Brunelleschi's time, including tensioners, metal pincers, rope-sizing devices, and the famous "ulivella". This tool, which had been lost during the Middle Ages, was originally used by the ancient Romans to lift massive stones. According to biographers, during his studies in Rome, Brunelleschi made a remarkable archaeological discovery: he found an original ulivella still embedded in a stone block among ancient ruins. Furthermore, it is interesting to observe that the machines, designed by Brunelleschi, along with the transported materials, had to be skillfully manoeuvred and assembled by expert workers. Only about sixty master craftsmen worked on the Dome under Brunelleschi's supervision. Aware of the dangers of working at such dizzying heights, the architect ensured that his workers could perform their tasks as safely as possible during the sixteen-year construction period (1420–1436). The history of the Dome's construction reveals that the genius of Brunelleschi and the boldness of the Opera del Duomo extended beyond engineering. As a matter of fact, these exceptional artifacts and their history could provide valuable insights into the production techniques and materials used during the Brunelleschi era. Drawings of similar tools appear in the works of Taccola, Francesco di Giorgio, Bonaccorso Ghiberti, Giuliano da Sangallo, and even in Leonardo da Vinci's Codex Atlanticus [8], [9].

Among the innovations utilized by Brunelleschi is the wooden chain that encircles the Dome, which contributes to its integrity. Some studies assert that the concept is adapted from the Baptistery of San Giovanni in Florence and from Middle Eastern domes [10]. The wooden chain, being an integral system of reinforcement, was initially designed to form part of an extensive system meant to prevent the Dome's possible collapse. Historical records indicate that this chain was constructed between 1423 and 1424 with various metallic joints composed of iron. Besides supporting the wooden beams, the metallic joints reflected the advanced metallurgical methods of the time. The complexity of these iron elements, including straps, bolts, and nails, betrays their importance in maintaining the Dome's structural integrity [10], [11].

In the Dome, other structural metallic elements are present. In particular, several metallic tie rods are found in the corridors of the second and third floors of the Dome itself.

Few studies have been conducted on the metal elements inside the Dome of Santa Maria del Fiore in Florence. In [12], cosmic ray muons were used to detect metal elements within the Dome's structure. In [10], [11] a study to date the elements of the wooden chain and localize the interventions over the years, including the metal connections, has been carried out. [13] discusses the application of advanced surveying technologies, such as laser-scanning, to investigate the internal structure of the Dome. These researches underline the importance of investigating the material and their interaction in the context of the Dome's historical preservation and structural stability.

Determining the provenance, materials, and production techniques of the tools and materials used for the Dome construction remains a challenge. In such cases, conservation science and engineering provide valuable methodologies for reconstructing their history. Restoration processes are very complex, considering that the original characteristics of historical buildings or sites must be preserved and that different professional figures, having different roles, responsibilities, and skills, are involved [14], [15]. Moreover, in the context of restoration and conservation of Cultural Heritage, it is crucial to extract experimental data to characterise the physical and chemical properties of the materials that constitute the archaeological and historical objects [16]. Tailored analytical strategies can be applied to examine the chemical composition and subsequently suggest appropriate conservation approaches [16]–[19].

Another interesting approach to tracking the studies performed on a specific site is the Heritage Building Information Modelling System (HBIM) [20], which consists of the realization of an information system for historical heritage using dedicated software, that integrates the data obtained by means of the performed optical non-destructive testing, particularly useful in the field of restoration, for the planning of the intervention, monitoring and subsequent use of the artefacts.

Building on earlier studies of the Authors on the Dome's construction tools preserved in the Museo dell'Opera del Duomo [21], [22], this paper reports on the second phase of a measurement campaign focused on the investigation of the alloys employed in the construction of the Dome. It extends previous findings, by including an analysis of a pulley preserved inside the Dome. In addition, a study on the metallic elements of the wooden chains and metallic embedded structures has been carried out. This paper provides a comprehensive survey of the constituent materials, exploring the potential role of different chemical elements in the alloys. The collected data have been further analysed using multivariate techniques to identify spectral similarities across different tools, offering new insights into their historical context and manufacturing techniques.

The findings from this study will not only contribute to our understanding of material use in Brunelleschi's design but also provide a comparative framework for assessing technological advancements in Renaissance construction practices.

1.1. The construction tools of the Museo dell'Opera del Duomo

In a preliminary study of the Authors [21], [22], XRF analysis was carried out on various tools from the collection of the Opera di Santa Maria del Fiore that are currently on display at the Museo dell'Opera del Duomo in Florence. These items include tools and equipment that were used in the construction of the Santa Maria del Fiore cathedral. The objects examined consisted of two turnbuckles, eight pulleys, two three-legged lewises, and a pincer (Figure 1).

The pulleys can be classified based on their appearance in two main typologies: the first group presents a wooden body with a metallic frame needed to hold and anchor the tool (PU-1, PU-2, PU-3, PU-4, and PU-5), and the second group is made entirely in metal (PU-6, PU-7, PU-8, and PU-9).

The composition was investigated by XRF, highlighting that the metallic frame of the wooden pulleys consists of an iron alloy containing iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), nickel (Ni), and traces of arsenic (As). The metallic pulleys present similar compositions, but the relative intensities of the characteristic peaks were different. Specifically, they were characterised by lower values of As and Mn. Some additional considerations have been extracted thanks to multivariate analysis. In particular, the

Figure 1. Historical tools employed for the construction of the Santa Maria del Fiore cathedral in Florence. From PU-1) to Pu-9) pulleys, P-1) pincers, L-1) and L-2) three-legged lewises, T-1) and T-2) turnbuckles.

main body of the metallic pulley PU-6 was identified as an iron alloy with a similar composition to the wooden pulley frame, but with the additional presence of lead (Pb). Eventually, the material of the wheels of metallic pulleys PU-7 and PU-8 was identified as lead bronze, characterised by the presence of Cu, tin (Sn), and Pb.

The two turnbuckles, used for lifting heavy loads, were also studied and represented an interesting case study. They are relevant both from the technical and historical point of view. Indeed, these tools were innovative for the Renaissance period, since they allowed smooth and controlled lifting of heavy loads and reduced the risk of chipping stones during positioning. Their depiction in Renaissance drawings, such as in the "Taccuino senese" by Giuliano da Sangallo [23], underlay their historical relevance. Structurally, turnbuckles consist of a central screw, nut, hook, and two connecting rods. The study [22] paid particular attention to the threaded components, as their material composition provides insight into Renaissance production techniques and dating. The analysis performed on turnbuckle T-1 revealed that the nut is made of a bronze alloy containing Cu, Sn, Zn, and Pb, along with trace elements such as Fe, Ni, antimony, and As. The presence of Zn, Ni, and Fe in lead bronze was already reported in previous studies [24], [25]. The presence of antimony (Sb) is interesting since it aligns with previous studies on artefacts of the Renaissance period, including the *Porta del Paradiso* reliefs by Lorenzo Ghiberti, where elements like antimony and arsenic were present as impurities in the alloys [26]. This compositional evidence supports the dating of T-1 to the era of Brunelleschi. The other components of T-1 are made of an iron alloy containing Cu, Zn, As, and Pb.

By contrast, the turnbuckle T-2 is exclusively composed of an iron alloy with a comparable chemical composition to T-1 but with Mn, Zn, and As higher concentrations. A difference in material composition like the one found in the two turnbuckles suggests differences in manufacturing techniques and possible differences in the period of manufacture. It is worth noticing that while bronze was commonly used during the Renaissance for threaded components due to its good machinability with steel tools, iron-threaded components suggest a later manufacturing period.

Finally, the pincers (P-1) and the lewises (L-1 and L-2), both used to lift stones, were made of an iron alloy, whose composition is mainly characterised by the presence of Cu, Zn, Ni, and As. Additionally, the lewises also presented Pb in their composition.

2. MATERIALS AND METHODS

2.1. Construction Tools

The study begun in 2020 covered the analysis of various tools associated with the construction of the Dome of the Santa Maria del Fiore Cathedral. The initial set of tools, constituted by 8 pulleys, 2 three-legged lewises, 1 pair of pincers, and 2 turnbuckles, was further enriched by a pulley stored within the Dome of the Santa Maria del Fiore (identified in this study as PU-9, see Figure 1). This pulley is constituted of 12 metallic wheels and a metallic frame needed to hang the tool and sustain the load.

The complete list of the analysed tools is reported in Table 1, indicating the identification code assigned in this manuscript.

Table 1. List of the construction tools analysed, with the indication of the number and the identification code assigned for this study.

Construction Tool	Number	Ident. Code
Pulleys	1	PU-1
	2	PU-2
	3	PU-3
	4	PU-4
	5	PU-5
	6	PU-6
	7	PU-7
	8	PU-8
	9	PU-9
Three-legged lewises	1	L-1
	2	L-2
Pincers	1	P-1
Turnbuckles	1	T-1
	2	T-2

2.2. Metallic Joints of the chestnut Chain in the Dome

In this Section, the metallic joints of the chestnut chain are described. In particular, the analyses were carried out in three different compartments in which the wooden chain was reachable,

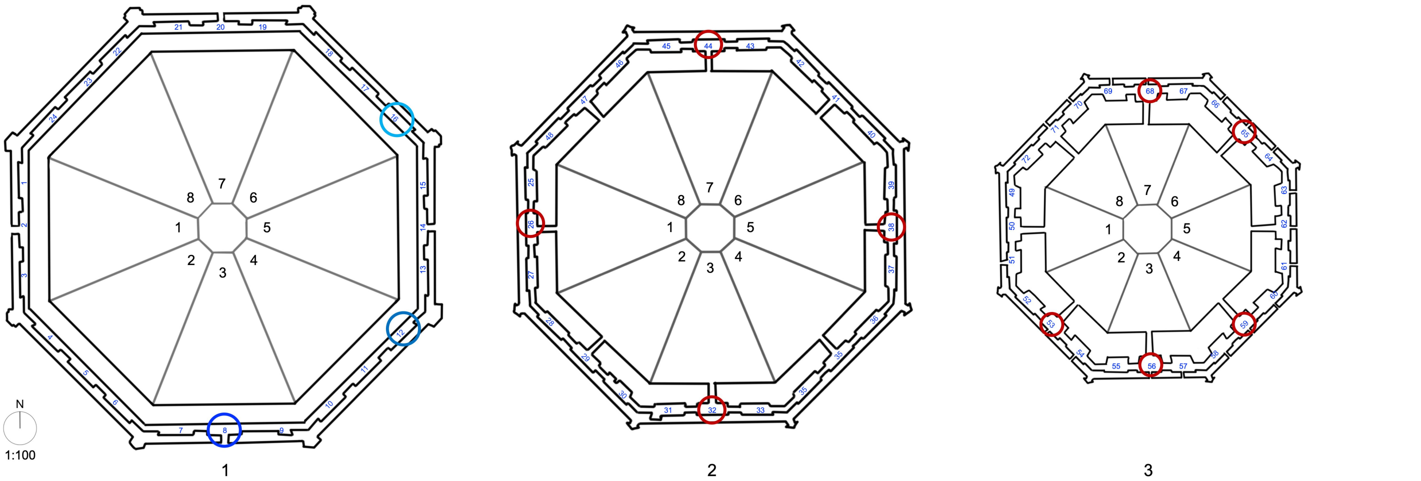

Figure 2. Plan (top view) of the first, second, and third floors. The analysis points in the compartments are highlighted in red. The analysis points carried out on the metal components of the chestnut chain, in compartments 8, 12, and 16, are marked in blue, light blue, and cyan respectively.

Figure 3. a) Metallic joint in compartment 8; b) Chestnut chain and metallic joint in compartment 12; c) Chestnut chain and metallic joint in compartment 16. The white letters indicate the areas of analysis; d) Compartment and the two metallic rods on the sides (white rectangles).

i.e. compartments 8, 12 and 16 (see Figure 2). In these compartments, the joints have different geometries and morphologies. More details, such as the location of the metallic joints and the identification code assigned in this paper, are reported in Table 2.

The metallic joints of the chestnut chain (Figure 3 a) located in compartment 8 - web 3, are datable back to the repairs that occurred in 1637 at the behest of the architect Gherardo Silvani. This involved the consolidation of the existing chestnut chain through the insertion of additional joints [10], [11]. Indeed, three iron rods can be observed superimposed on the original hoop, equipped with an eyelet at the ends and connected to each other by means of a "hinge" joint, i.e. by overlapping the eyelets of two adjacent rods and inserting a vertical rod as a blocking element. The latter, crossing the chain at its entire height, also guarantees the vertical connection between the elements, fixing the new metal tie rods to the pre-existing wooden beams. The chestnut chain is covered by a sheet of copper, which makes it difficult to observe additional elements of connection. This type of joint is present in two occurrences within the structure [10], [11].

Table 2. List of the compartments in which the metallic joints of the chestnut chain have been analysed, with the indication of the compartment in which they are located, the areas of analysis (see Figure 3) and the identification code assigned for this study.

Compartment	Area of analysis	Ident. Code
8	A	J8-A
	B	J8-B
	C	J8-C
	D	J8-D
12	A	J12-A
	C	J12-C
	D	J12-D
16	A	J16-A
	B	J16-B
	C	J16-C
	D	J16-D
	E	J16-E
	F	J16-F

Another type of joint of the chestnut chain is characterised by the use of wood beams connected through a metal banding. This joint consists of wooden beams secured together using nails. The beams are supported by an iron pin, which ensures the joint's stability, while the iron banding reinforces the connection. It is the most widespread and remains largely authentic. The dating of this joint is placed in the early period of the Dome's construction, making it an important example of the construction techniques used in the 15^{th} century. There are 18 instances of this joint type identified on the chain [10], [11]. In this study, the metallic joints

Table 3. List of the compartments in which the metallic rods have been analysed, with the indication of the floor where they are located, the number of the compartment and the identification code assigned for this study.

Floor	Compartment	Ident. Code
2	26	C2-26
	32	C2-38
	38	C2-38
	44	C2-44
3	53	C3-53
	56	C3-56
	59	C3-59
	65	C3-65
	68	C3-68

of the chestnut chain located in compartment 12 of web 4 have been analysed (Figure 3b).

The other type of joint analysed in this study appears quite complex and includes both vertical and horizontal connection elements. Two large U-shaped brackets ensure the vertical connection between the wooden elements (the chain and the underlying corbel). An interesting feature is that the brackets are closed at the upper end by threaded bolts. A metal tie rod with an eyelet terminal and an iron wedge reinforces the horizontal connection between adjacent beams. The system is completed by two metal plates nailed to the beam to ensure a stronger anchoring between the tie rod and the wooden beam, as well as among the various metal components [10], [11]. This typology is found in 4 locations in the Dome. In this paper, the one in compartment 16 of web 6 was analysed (Figure 3c).

2.3. Metallic rods in the Dome

The second and third corridors within the Santa Maria del Fiore Dome situated within the double-shell structure, include several compartments in which *oculi* (from the Latin 'eye'), circular apertures, were realised, serving dual purposes: facilitating light diffusion into the interior and reducing the dome's weight. Several metal elements are embedded within the walls of the compartments along the corridor and they have been analysed in this study, as reported in detail in Table 3.

Figure 3d reports a representative image of one of the compartments mentioned in this section. The surface of the metal rods was cleaned before analysis to remove the superficial layer of corrosion products, to highlight differences in the bulk composition of the components.

2.4. X-Ray Fluorescence Spectroscopy (XRF)

The artefacts were analysed by XRF Spectroscopy to investigate their elemental composition, using a Bruker Tracer 5i spectrometer (20 mm^2 silicon drift detector; Rhodium (Rh) anode) that allows for in-situ and non-invasive analysis. A titanium-aluminium (Ti-Al) filter was employed to reduce the intensity of peaks associated with Rh and palladium (Pd). The analyses were performed using the following parameters: voltage of 40 kV, current of 40 μA, using a 3 mm collimator. The spectra were processed with Artax Spectra (8.0.0.476) software.

2.5. Principal Component Analysis (PCA)

Acquired spectra were processed by means of Principal Component Analysis (PCA), which can investigate similarities among the alloys, identify patterns and classify spectra in different groups [27]. PCA was performed on the XRF spectra using a Python script, as described in [22], by means of the Scikit-learn library. Spectra were pre-processed before PCA as follows. First, the interval of interest was limited to the range from 1 keV to 12.2 keV, i.e. including only the relevant part of the spectra in the PCA, where all significant peaks are present. Then, the baseline was subtracted using the Artax Spectra software. The Savitzky-Golay filter was used to improve signal-to-noise ratio [28], with a second-order polynomial and a 90 eV window length to avoid any over-smoothing. Spectra were normalized using the Standard Normal Variate Transformation (SNVT) [29]. Eventually, principal components were computed and results were graphed as biplots, in which eigenvalues for different spectra were plotted.

3. RESULTS AND DISCUSSION

3.1. Construction tools

Figure 4 shows representative XRF spectra collected on the pulleys: on the metallic frame of the wooden pulleys PU-2, the main body of the metallic pulleys PU-7 displayed in the museum, and the main body of the metallic pulley PU-9 stored in the Dome.

From the spectra, the material of the pulleys can be identified as an iron alloy. Indeed, two main peaks at 6.40 keV and 7.06 keV correspond to characteristic Kα and Kβ lines of iron respectively. The material is then characterised by the presence of manganese, copper, zinc, nickel, and tin demonstrated by the presence of peaks at 5.90 keV (Mn-Kα), 8.05 keV (Cu-Kα), 8.64 keV (Zn-Kα), 7.48 keV (Ni-Kα), and 25.27 keV (Sn-Lα) respectively. Finally, it is possible to identify sulfur (2.3 keV, S-Kα), chlorine (2.62, Cl-Kα), argon (2.95, Ar-Kα), calcium (3.69 keV, Ca-Kα and 4.01 keV, Ca-Kβ), potassium (K-Kα 3.31 keV); these are present in all acquired spectra and can be related to environmental contamination. The triplet peaks 12.81 keV (Kα + Kα), 13.46 keV (Kα + Kβ), and 14.12 keV (Kβ + Kβ) can be attributed to iron sum peaks, while the ones at 4.67 keV and 5.32 keV can be assigned to the Fe-K lines escape peaks. The peaks of Kα and the Kβ lines related to the rhodium anode are present at 20.22 keV and 22.72 keV respectively. The broad peak at 19.06 keV can be attributed to the Rh Compton scattering and the peak at 1.48 keV to the Kα of Al. These peaks are due to instrument contribution. Also arsenic is present, as can be seen from the presence of the peaks at 10.54 keV (Kα) and 11.72 keV (Kβ). The peak at 10.54 keV could be assigned also to the Lα of lead (Pb), but the K shell intensity ratios (Kβ/Kα) is respected for As, with an average value close to 0.14 [30], suggesting the absence of Pb. As was often present in iron alloys as it was a common contaminant in iron ores [31], [32]. Among the different pulleys, it is worth noticing that the relative intensity of peaks changes. In particular, the metallic pulley exhibited at the museum (PU-7) and the one stored in the Dome (PU-9) have similar intensities, while the wooden pulley presents a lower concentration of Cu and Zn.

To study in deep this aspect, and to identify any difference among the pulleys, PCA was performed. A preliminary multivariate processing on the data of the pulleys stored in the museum had been carried out by the Authors in [22], highlighting that higher values of arsenic and manganese characterised the wooden pulleys, while the metallic pulleys were characterised by a higher concentration of zinc. The data were processed again including also the spectra acquired on PU-9, to identify any similarities or discrepancies in the composition of the artifacts. The results are reported in Figure 5, where notably the PU-9 score points fall within the same group as the metallic pulleys stored in the museum, suggesting similar composition among the iron-alloys.

3.2. Metallic joints of the chestnut chain in the Dome

Figure 6, Figure 7, and Figure 8 show the XRF spectra collected on the metallic joints of the wooden chain in compartments 8, 12, and 16 respectively.

The material composition is attributable to an iron-alloy. Several elements have been identified by the following characteristic peaks: iron (6.40 keV, Kα and 7.06 keV, Kβ) is the main element, followed by the presence of minor elements such as Mn (5.90 keV, Kα), Cu (8.05 keV, Kα), Zn (8.64 keV, Kα), Ni (7.48 keV, Kα), As (10.54 keV, Kα and 11.72 keV, Kβ), and Sn (25.27 keV, Kα).

The peaks of S (2.3 keV, Kα), Ar (2.95 keV, Kα), Ca (3.69 keV, Kα, and 4.01 keV, Kβ), and K (3.31 keV, Kα) can be related to environmental contamination.

Fe sum peaks are present at 12.81 keV (Kα + Kα), 13.46 keV (Kα + Kβ), and 14.12 keV (Kβ + Kβ), while Fe-escape peaks at 4.67 keV and 5.32 keV. The following peaks due to instrument contribution were identified: Al (1.48 keV, Kα), Rh (20.22 keV, Kα and 22.72 keV, Kβ), Rh Compton scattering (19.06 keV).

The elemental composition is comparable among all the joint of the wooden chain. Differences have been detected only regarding the relative intensities of some elements. In particular, in J-16, the threaded bolt (point B) and the two metal plates nailed to the beam (point C) present higher concentrations of Cu and Zn.

Similarly, comparing points A and B or the J-8, a higher concentration of Cu and Zn is detected in point B, namely on the vertical iron rods.

3.3. Metallic rods in the Dome

The spectra of the iron rods are attributable to an iron alloy. The most intense peaks at 6.40 keV and 7.06 keV correspond to the Kα and Kβ lines of Fe. The presence of Mn, Cu, Zn, and Ni is confirmed by peaks at 5.90 keV (Mn-Kα), 8.05 keV (Cu-Kα), 8.64 keV (Zn-Kα), and 7.48 keV (Ni-Kα), respectively. Also in this case, the presence of S (2.3 keV, Kα), Ar (2.95 keV, Kα), Ca (3.69 keV, Kα, and 4.01 keV, Kβ), and K (3.31 keV, Kα) could be due to environmental contamination. Iron-sum peaks are observed at 12.81 keV (Kα + Kα), 13.46 keV (Kα + Kβ), and 14.12 keV (Kβ + Kβ). The peaks at 4.67 keV and 5.32 keV correspond to Fe-K escape lines. Furthermore, Al (1.48 keV, Kα) and Rh (20.22 keV, Kα and 22.72 keV, Kβ) are due to the instrument contribution. The broad peak at 19.06 keV is linked to the Compton scattering of Rh characteristic photons.

PCA was used to investigate any similarities among the composition of the several compartment tie rods. The obtained score and loading plot are reported in Figure 10. The results did not indicate any relevant differences in the iron alloy composition of the metal rods. The PCs have a high degree of overlap with no distinct clustering among samples. Thus, the are no significant

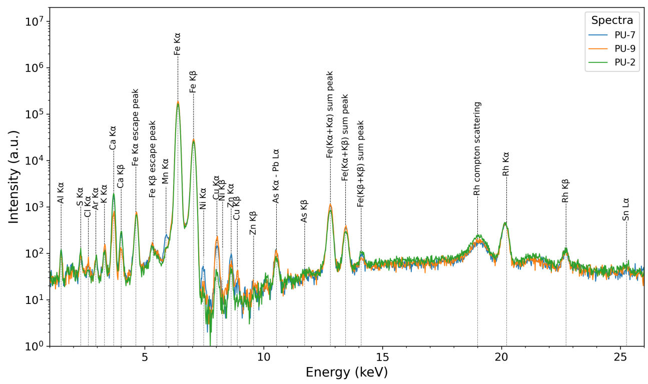

Figure 4. X-Rays Fluorescence spectra collected on the pulleys: on the metallic frame of the wooden pulleys PU-2, the main body of the metallic pulleys PU-7 displayed in the museum, and the main body of the metallic pulley PU-9 stored in the Dome.

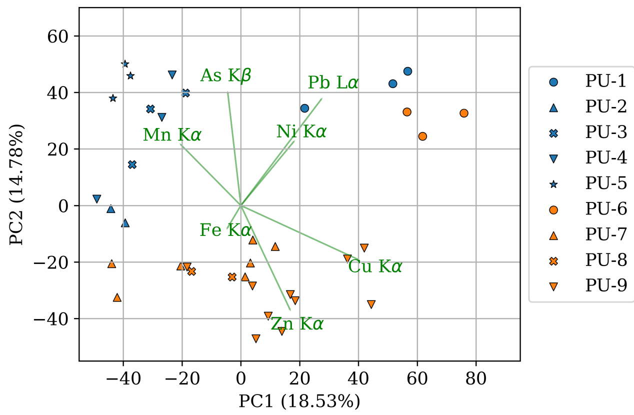

Figure 5. Score and loading plot of the components PC1 and PC2 computed from the XRF spectra acquired on the pulleys. The percentage variance of each PC is reported along each axis.

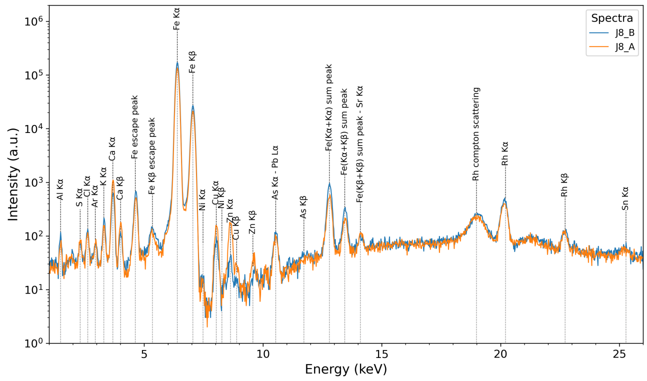

Figure 6. X-Rays Fluorescence spectra collected on the joints of compartment 8, in points A and B.

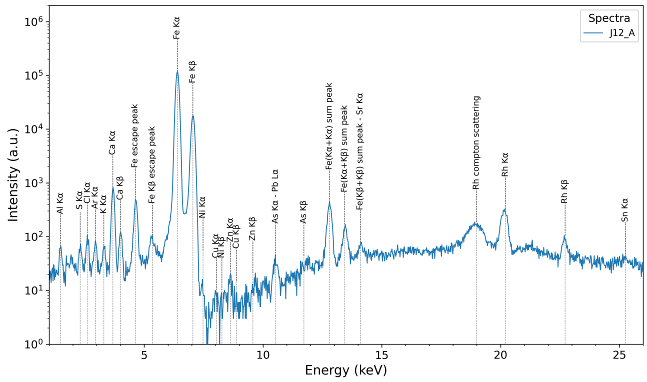

Figure 7. X-Rays Fluorescence spectrum collected on the joints of compartment 12, in point A.

discrepancies in the intensities of the alloy characteristic peaks, indicating compositional uniformity across the analysed areas.

4. CONCLUSIONS

The present study is the first to analyse the elemental composition of the metallic construction tools and elements used in constructing the Dome. XRF spectroscopy provided a non-invasive tool to explore the metallurgical practices of the Renaissance, revealing the material composition of key structural components in the Dome. While XRF alone cannot date the artifacts, combining the elemental analysis with historical sources could offer valuable insights into the technologies and materials employed

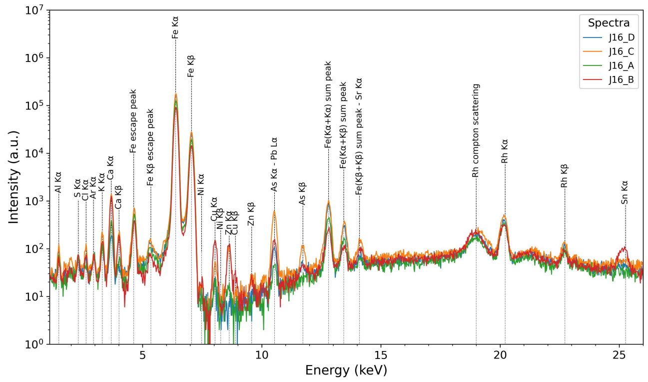

Figure 8. X-Rays Fluorescence spectra collected on the joints of compartment 16, in points A, B, C, and D.

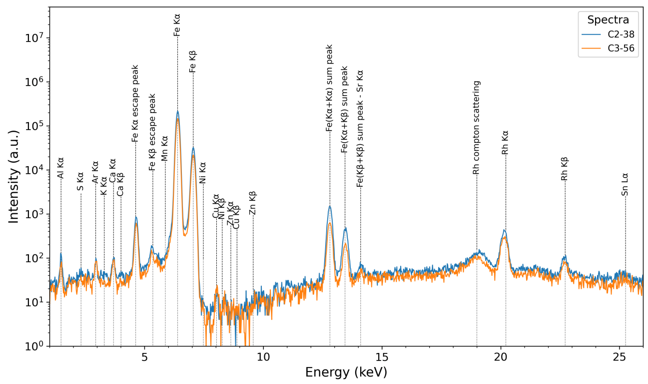

Figure 9. Representative X-Rays Fluorescence spectra collected on the metallic rods of the second and third floors.

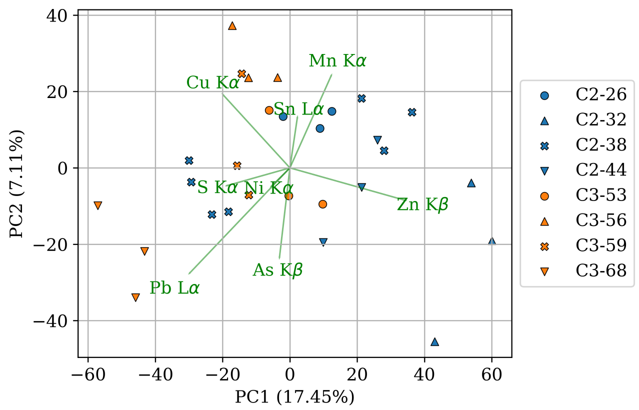

Figure 10. Score and loading plot of the components PC1 and PC2 computed from the XRF spectra acquired on the metallic rods of the Dome compartments. The percentage variance of each PC is reported along each axis.

during Brunelleschi's time. The experimental findings contribute to both historical knowledge and conservation efforts for the iconic Dome. The study successfully identified the materials used in pulleys, joints, and rods within the Santa Maria del Fiore Dome. As an overall consideration, this monitoring campaign not only contributes to shed light on the construction methods of Brunelleschi's Dome but also provides crucial data for the preservation of this architectural marvel. Understanding the material composition used by Brunelleschi enhances our historical comprehension and helps safeguard the integrity of the Dome for future generations.

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