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Lorenzo Nottolini's architectural heritage in Tuscany. Digital twins and database for restoration project management.

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Abstract. The article examines methodologies for developing digital databases and digital twins as tools for the restoration and protection of architectural heritage. The focus is on the Aqueduct of Lucca, designed by Lorenzo Nottolini beginning in 1822, a complex work of significant historical and architectural value. The research combines the analysis of archival and bibliographic sources with advanced laser and photogrammetric survey techniques to create detailed three-dimensional models. The study of this case provides an opportunity to apply the described approach to a concrete example, utilizing both direct and indirect analyses. Through this inductive method, it will be possible to derive more general guidelines.

Keywords: Lorenzo Nottolini, Restoration, Digital twins.

1 Introduction

The aim of this research is to develop methodologies for the creation of digital databases and digital twins as fundamental tools for defining guidelines for restoration projects and the protection of architectural heritage [1]. This study seeks to reconstruct the work of architect Lorenzo Nottolini by comparing archival sources with the current state of his works. Despite the wealth of archival material and bibliographic production on the architect, a comprehensive and detailed analysis of his work is still lacking. This study serves as a unique case to develop methodologies for creating digital tools for the restoration and protection of historical heritage. The following article presents the first outcome of the research carried out so far.

The detailed study presented here offers the opportunity to test these methodologies on a specific case study: the Aqueduct of Lucca, designed by Nottolini beginning in 1822. Despite its aesthetic and formal simplicity, the Aqueduct is one of the most complex architectural-engineering works realized by the architect from Lucca, considering its design, historical vicissitudes, and current conservation problems. The examination of this case provides a chance to apply the described approach to a concrete example, utilizing both direct and indirect analyses. Through this inductive method, it will be possible to derive more general guidelines.

Fig. 1. Lucca, acquedotto del Nottolini, vista aerea del doppio condotto su archi, 2023.

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2 The aqueduct of Lucca, historical compendium

The work on constructing the digital database began with the collection and cataloging of archival material produced by Nottolini. Alongside the archival documentation, an examination of the existing bibliography on the subject was conducted. Through the study of the collected information, it was possible to reconstruct the history and events that characterized the construction of the aqueduct.

Until the early 19th century, Lucca's water supply for daily needs relied on town wells located in various strategic places around the town [2]. However, the water from these wells contained high concentrations of selenite, which caused liver damage, and neglect and poor maintenance often led to plagues [3]. Even today, traces of these ancient wells and their former locations can still be found in the city. One of the first attempts to bring water into the town from external springs occurred on 5 September 1732 [4], but the first significant step in realizing this ambitious project dates back to 13 May 1763, when the General Council approved a report drawn up by six citizens of Lucca, proposing to the Government of the Republic to use water from Guamo [5].

On 24 December 1763, abbot and mathematician Giovan Francesco Giusti presented a report that made the first substantial contribution to the design of the aqueduct. After inspecting the proposed springs, which were excellent both in terms of location and water quality, the abbot submitted a report with an attached project proposal to the Council. Giusti proposed an aqueduct *"like that of the Romans, followed by the Pisans and other cities, i.e., to support the conduit above the arches, as the water flows and purifies itself by depositing the impurities, and does not exert any pressure inside the conduit, thus helping to keep it in excellent condition"* [6]. On 28 August 1772, the General Council appointed Giovan Attilio Arnolfini to further the studies initiated in previous years and to advance the completion of the aqueduct [7]. The Council examined Arnolfini's project on several occasions without ever making a final decision [8].

In 1809, during the principality of Élisa Baciocchi, the construction of the aqueduct was decreed, and three projects were presented. Among these was a project submitted on 15 August 1810 by the French engineer Carlo de Sambucy, which envisaged the construction of a large cistern to purify the water from the springs and a double conduit positioned on arches with a buttress every fifteen spans. On 14 February 1812, the project was approved, and work began on connecting the first springs by fixing the line of arches. However, the building site stopped in 1813, as the engineer, considered partly responsible for the overflowing of the Serchio river, was relieved of his duties [9].

After the Congress of Vienna (1814-1815), various reigns took place in Lucca. In 1817, the Bourbon dynasty took office, and Maria Luisa of Bourbon-Spain (1782-1824) became the reigning duchess of the duchy's capital. On 25 September 1822, Nicolao Giorgini, gonfalonier of the duchy, presented a report and a new project signed by the state engineer Giuseppe Valentini. By order of 7 October 1822, the Duchess decreed the construction, and the engineer was entrusted with the direction of the work [10].

The project drawn up by Valentini did not differ substantially from those of his predecessors, so much so that it was described by Mazzarosa as *"inferior, not only to the first project but also to that of Sambucy in terms of art and usefulness"* [11]. Even Duchess Maria Luisa was not fully convinced by the project, so Lorenzo Nottolini was commissioned to make further proposals. Thus, on 31 October 1822, Maria Luisa issued a further order that confirmed the direction of the works to the engineer Valentini but also entrusted the superintendence to the architect Nottolini [12].

In 1829, Gonfaloniere Giorgini, in a letter to his close cabinet secretary Navasquez, described the changes made to the project, pointing out not only the raising of the duct and the increase in the width of the spans but also Nottolini's decision to interrupt the duct near the walls [13].

On 13 March 1824, Charles Lodovic of Bourbon (1799-1883) succeeded his late mother, Marie Louise. On 15 April 1824, on the advice of the city's Gonfalonier and due to financial problems related to the cost of building the aqueduct, he suspended work until further notice. Despite this, work resumed in 1824 with considerable effort to complete the arches. However, at a meeting held on 24 February 1825, objections were raised to the project, particularly regarding the decision to introduce water into the city through a penstock. The Royal Architect responded to the criticism, addressing both technical concerns and emphasizing the importance of preserving the historical environment. Nottolini stated, *"the most pleasant walkway in our city after the walls is that of the Spalto that surrounds them, so it must be the main concern of those who nurture the idea of beauty to preserve it in all its parts"* [14].

Nottolini was also concerned with designing a crucial detail: the *Serra vespaiata*. Through its construction, the architect aimed to unite all the waters of the Rio San Quirico and Rio di Valle, thereby

increasing the volume of water brought to Lucca. This unique structure exemplifies Nottolini's ingenuity in the realization of the aqueduct, considering every detail [15].

Towards the end of 1827, the construction of the arches above the plinth for the entire length was completed. To interrupt the monotony of a completely uniform structure and, in particular, to increase its stability, Nottolini, probably inspired by Sambucy's project, decided to build a buttress every 17 arches, resulting in a total of 26 reinforcements.

Fig. 2. Diagram of the Lucca aqueduct system.
1. The city fountains 2. The penstock 3. The terminal temple of San Concordio
4. The double conduit on arches 5. The initial temple of Guamo 6. Underground conduit
7. The system of fountains and the *serra vespaiata*

The work continued until 1832, despite numerous criticisms and bureaucratic hiccups. Although there are no documents in the archives that provide a precise date for the commissioning of the aqueduct, it can be placed in this year [16]. The first report was made by Nottolini himself on 16 September 1832, where he identified problems with the springs connected during French rule [17].

The incident clearly gave the detractors of the Royal Architect fresh impetus, placing him once again at the center of an intense and bitter controversy. On 24 January 1833, Nottolini was therefore compelled to join Carlo Lodovico in Berlin to clarify his position [18]. After carefully listening to the Royal Architect, the Duke appointed a new commission, composed of Michele Bertini and Giovanni Pacini, in a letter dated 4 March. Their task was to assess Nottolini's work and identify the cause of the cloudy waters [19].

Nottolini's management of the works received a positive evaluation from the commission, while several technical remarks were directed at the first commission [20]. The Royal Architect was thus relieved of the charges against him, and a royal decree dated 18 September 1833 reaffirmed Lorenzo Nottolini's direction of the works, also assigning him the task of drawing up the plans for the network's branches in the city. In the following years, various projects were undertaken to extend the water network by rebuilding several conduits, sewers, and fountains in the city. By 1838, the aqueduct, which Wiebeking described as one of the "most valuable monuments in Italy" [21], was completed. The Royal Architect himself was appointed to direct the maintenance of the structure, a responsibility he held until his death in 1851.

Following Nottolini's passing, the management of the aqueduct did not encounter significant difficulties. Architect Cesare Lazzarini, head of the municipal technical office, was appointed to oversee all aspects of the aqueduct. During this period, it became evident that extending buffer zones around the springs was crucial for their protection. Engineer Luigi Pasquini was therefore tasked with assessing the necessary land acquisitions and surveying the aqueduct's route from the *Serra vespaiata* to the San Colombano bastion, identifying all cadastral properties near the monument [22].

Over the years, numerous interventions were carried out, including pipeline repairs and replacements, adaptations to the distribution system, and studies and analyses on water quality, among others. As time passed and the population's needs evolved, the aqueduct gradually lost its functional importance while remaining a vital symbol for the Lucchese community. The water supply issues in Lucca and its surroundings were resolved after the First World War with the establishment of the civic aqueduct. In 1928, the decision was made to abolish the old water concessions from Guamo [23].

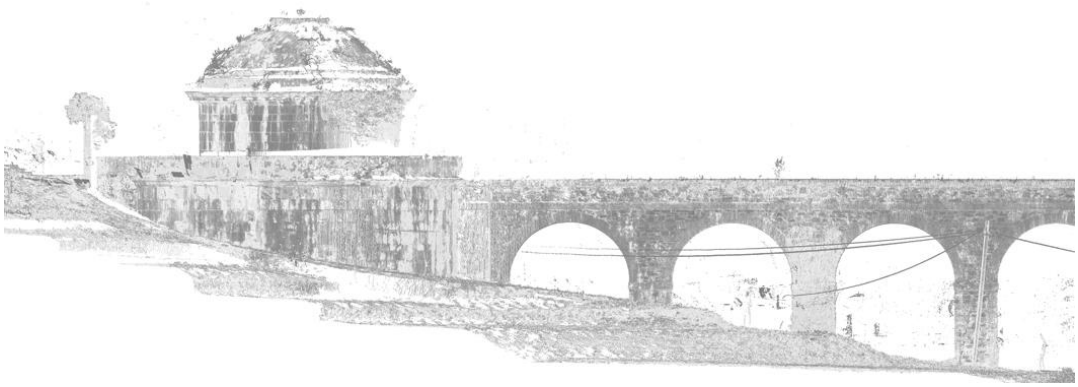

Fig. 3. Lucca, Tempietto di Guamo, orthoimage of the point cloud obtained from the laser scanner survey.

During these years, significant changes occurred to the aqueduct, particularly to the arched conduit. Between 1928 and 1932, the construction of the A11 motorway section connecting Florence to Pisa led to the demolition of a pillar and the construction of an archway that differed completely from the others, allowing passage for the new infrastructure. This same section was destroyed in 1944 by the retreating German army to impede the advancing Allied forces [24].

Later, in 1962, the motorway underwent expansion, necessitating the complete interruption of the previously modified section with the demolition of five additional pillars. This intervention caused structural issues, including noticeable horizontal cracking and longitudinal deformation [25].

Today, the aqueduct is accessible to the public via pedestrian and bicycle paths, allowing visitors to stroll along the arches and admire both the monument and the surrounding landscape. The municipality has also scheduled a series of interventions along the route to enhance accessibility [26]. Additionally, the area around the springs, known as the Golden Words, is open for visitors to explore.

3 Towards a digital twin

As evident from the preceding paragraph, the initial step in constructing a database involves systematically gathering all relevant documents related to the research topic. These may include historical documents, drawings, bibliography, published sources, photographic images, and contemporary records. This initial review of the state of the art is essential for structuring the database, understanding the types of documents to be archived, defining associated descriptive information (metadata), and estimating the volume of information to be archived to properly design the infrastructure.

The history of the Aqueduct of Lucca spans approximately three hundred years, encompassing numerous characters and events. Consequently, there exist many sources documenting the history of this artifact. The collected data has been organized into a database using FileMaker software, chosen for its flexibility in managing diverse types of data.

This approach also facilitates the future development of the final database structure in accordance with the FAIR principles for research data management. In recent years, information and documentation management has become a topic of crucial importance for the global scientific community. The FAIR principles (Findable, Accessible, Interoperable, Reusable) were developed to enhance the discovery, access, interoperability, and reuse of scientific data, thereby promoting a more efficient and transparent research ecosystem. These principles were initially published in a foundational document in 2016 and have since gained widespread adoption [27]. Managing information according to these principles not only enhances the reproducibility and transparency of research but also increases the value of the data itself, transforming it into a valuable resource for researchers and scholars. However, implementing these principles can be challenging, particularly with sources collected from public and private historical archives. These archives often have their own rules and regulations for publishing and sharing documents, which may conflict with the FAIR principles.

During the data collection phase, a direct comparison with the artifact was conducted concurrently. In the case of the Aqueduct of Lucca, the research group from the Department of Architecture at the University of Florence [28] performed various studies and analyses, including the acquisition of geometric and

dimensional data. This involved conducting laser scanners and photogrammetric surveys to capture both morphological and material-colorimetric information.

From the resulting three-dimensional models, two-dimensional data were extracted and used to create thematic tables that explore the surface characteristics of the materials and their degradation. This step is crucial for developing a digital twin. The morphological-geometric information of the artifact forms an essential foundation for creating a comprehensive three-dimensional model that integrates all collected information, ranging from historical documents to detailed physical-material data and the current state of conservation of the artifact.

4 Conclusion

The methodological approach followed enabled a critical framing of the subject and identification of the distinctive characteristics necessary for creating a digital twin. Digital twins represent a powerful tool for establishing restoration guidelines and developing proactive conservation plans. However, there remain significant practical and theoretical limitations. Despite the concept being explored across various domains, a definitive and universally accepted definition of a digital twin remains elusive. Specifically within architecture and civil engineering, digital twin implementation is still in its nascent stages and primarily confined to experimental projects. Furthermore, defining a digital twin within the realm of built heritage conservation is particularly ambiguous [29]. In essence, a digital twin of an architectural artifact is a dynamic and interactive digital representation of the physical object, incorporating real-time sensor data, detailed three-dimensional models, and comprehensive structural and functional information.

The Aqueduct of Lucca serves as an exemplary case due to its formal simplicity that belies underlying complexities. As previously emphasized, this artifact, which spans a territorial-landscape scale, comprises various components differing in morphology, location, and function. Following the conducted studies and analyses, it is evident that the arched duct, undoubtedly the most monumental part of the structure, cannot be considered separately from the system of fountains with the *Serra vespaiata* designed by Nottolini, the small temples positioned at the duct's boundaries, and the network of city fountains.

Digital twins represent a significant advancement in the tools available for conservation and restoration, introducing new methodologies for managing and monitoring artefacts. However, it is essential to consistently refer to the foundational theoretical principles of restoration, various investigative methodologies, and established operational practices. This promotes a continuous dialogue between technical expertise and critical thinking.

References

1. Terras M., Digital images for the information professional, Ashgate Publishing, Ltd., 2008; Millar L. A., McKemmish S., From digitization to e-research: Transforming the experiences of archival users, Archival Science, vol. 10, n. 4, 2010.
2. Salvetti C., L'acquedotto di Lorenzo Nottolini, Lucca, Maria Pacini Fazzi Editore, 1987, pp. 9-10; Bedini G., Dai pozzi alle fontane della città, in Bedini G. (a cura di), Lucca, il paesaggio e l'architettura dell'acqua, Lucca, PubliEd, 2004, pp. 108-117.
3. Mazzarosa A., Descrizione dell'acquedotto di Lucca, Tipografia Giusti, 1837, Lucca, p. 3.
4. Romiti V., Gli acquedotti di Lucca, storia e vicende, in «Rivista archeologia, storia, costume», 4, ottobre - dicembre, 1988, p. 30.
5. Archivio di Stato di Lucca, Deputazione sopra le Fontane di Lucca, Nota numero 1, Filza numero 1.
6. Salvetti C. 1987, pp. 9-10.
7. Mancini A., Storia di Lucca, Maria Pacini Fazzi Editore, Lucca, 1975, p. 274.
8. Archivio di Stato di Lucca (ASLu), Deputazione sopra le Fontane di Lucca, Nota numero 1, Filza numero 1.
9. Bongi S., Inventario del Regio Archivio di Stato a Lucca, volume III, Lucca, Tipografia Giusti, 1872, p. 247.
10. Archivio Storico Comunale di Lucca (ASCLu), Raccolta delle Leggi e dei Decreti del Ducato dei Borboni.
11. Mazzarosa A., Sulle opere e sui concetti dell'arch. e ing. L. Nottolini, Lucca, Tipografia Giusti, 1856, p. 7.
12. ASLu, Reale Intima Segreteria, filza 132, n. 948.
13. ASLu, Reale Intima Segreteria, filza 231, n. 831.
14. Pacini G., Storia degli Acquedotti lucchesi, Lucca, Tipografia Giusti, 1834, p. 23.
15. ASCLu, Commissione sui pubblici acquedotti, Busta n. 1, 25 settembre 1822 – 23 febbraio 1825, protocollo n. 331.

16. Some documents at the State Archive of Lucca indicate the day of Corpus Domini, while according to Mazzarosa, this date should be placed on June 21, 1832; cfr. Salvetti C. 1987, p. 28.
17. ASCLu, Commissione sui pubblici acquedotti, Busta n. 4, 31 luglio 1831 – 27 marzo 1833, protocollo n. 1404-1407.
18. ASLu, Registro delle gite, Carte Nottolini, 1831 n° 20.
19. ASLu, Reale Intima Segreteria, filza 269, n. 208.
20. Bertini M., Pacini G., Voto del profess. M. Bertini e G. Pacini emesso in conformità del Sovr. Veneratiss. Decreto del 4 marzo 1833 sui lavori eseguiti e da eseguirsi intorno alle fonti lucchesi a seconda dei piani del R. Architetto Lorenzo Nottolini, Tipografia Giusti, Lucca 1833.
21. Salvetti C. 1987, p. 38. Further evidence of Wiebeking's visit to the aqueduct can be found in Nottolini's Diary of Excursions, where the architect notes two site visits to the aqueduct with the German artist on July 2, 1838, and April 3, 1841. ASLu, Registro delle gite, Carte Nottolini, 1831 n° 20. The aqueduct, particularly the double conduit on arches, consists of 459 full-arch spans, 460 rectangular-section pillars made of mixed stone and brick masonry, and 26 buttresses, totaling approximately 3250 meters.
22. ASCLu, Fondo mappe, Cartella Acquedotto Nottolini.
23. ASCLu, Delibera Podestà n. 1623 del 24.11.1928, n. 295 del 6.3.1929, n.374 del 26.3.1929, n. 516 del 26.4.1929.
24. Salvetti C. 1987, p. 53.
25. On the structural behavior of the aqueduct cfr. Campani V., Berti G., Tanganelli M., Viti S. (2016), Valutazione del comportamento strutturale dell'acquedotto monumentale di Lucca, tempietto di San Concordio, in Parriniello S., Besana D. (a cura di), IV Convegno Internazionale sulla documentazione, conservazione e recupero del patrimonio architettonico e sulla tutela paesaggistica, Edifir, Firenze, pp. 1-10.
26. In 2014, the Municipality of Lucca promoted and implemented a comprehensive project in collaboration with the Municipality of Capannori, titled "From the sources to the fountains," aimed at enhancing Nottolini's aqueduct through the creation of a cycling and walking path. The final project was presented and approved in October 2022.
27. Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., et al, The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, 3, 2016. doi:10.1038/sdata.2016.18; for further insight into the topic cfr. FORCE11. The FAIR Data Principles, 2021; Open Access Government, The FAIR principles: Trusting in FAIR data repositories 2023; NIST, FAIR Data Principles, 2024.
28. The research group, coordinated by Susanna Caccia Gherardini and professore Giovanni Minutoli, è composto da Paola Bordoni, Iacopo Campinoti, Gianluca Fenili, Giorgio Ghelfi, Francesca Giusti, Pierpaolo Lagani, Francesco Pisani, Adele Rossi; cfr. Caccia Gherardini S., Classicità a filo d'acqua: l'acquedotto di Lorenzo Nottolini. Studi e indagini per la Conservazione, in Rueda Márquez De La Plata A., Cruz Franco P. (a cura di), Los cuadernos del ReUSO. La gestión territorial y el problema de la conservación de los centros históricos y el paisaje, Atti del convegno ReUSO Caceres 2023, Caceres 18-21 ottobre 2023, Dykinson.
29. Sharma, A., E. Kosasih, J. Zhang, A. Brintrup, and A. Calinescu, Digital twins: State of the art theory and practice, challenges, and Open Research Questions, 2020, no. December. http://arxiv.org/abs/2011.02833. Per una bibliografia aggiornata sui digital twins cfr. Vuoto, A., Funari, M. F., & Lourenço, P. B., Shaping Digital Twin Concept for Built Cultural Heritage Conservation: A Systematic Literature Review. International Journal of Architectural Heritage, 2023, 1–34. https://doi.org/10.1080/15583058.2023.2258084.