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A Digital Approach to Filigranology

The Case Study of the DRACMarkS Project at the Austrian Academy of Sciences

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ABSTRACT

Watermarks have been used as certificates of quality and provenience of handmade paper since the 13th century. They are at the centre of a dedicated discipline, filigranology, which, along with bibliography and history, attempts to apply paper studies to the dating of chronologically unclear manuscripts and printed sources. The present dissertation will focus on the recent encounter between watermark research and digital humanities, creating new perspectives for the registering, archiving and analysis of paper for bibliographical purposes. It is at this intersection that the project on Digitisation, Recognition, and Automated Clustering of Watermarks in the Music Manuscripts of Franz Schubert (DRACMarkS) operates and progresses. By implementing the use of a thermographic camera for watermark reproduction and ensuring long-term data access with the use of XML files structured according to the standards of the Music Encoding Initiative (MEI), the project aims to compare resulting images using signal processing methods. After having precisely described each step of the digitisation process, the thesis will underline the strengths and weaknesses of the chosen techniques, focussing on their future developments. The possibility of identifying similar or identical watermarks contained in Franz Schubert's autographs will, in fact, support future research on the composer's undated manuscripts and, more generally, on the European paper trade at the beginning of the 19th century.

Keywords: Watermarks, digital humanities, digitisation, thermography, Franz Schubert

INTRODUCTION

Paper, one of the most common materials in modern life, has been the primary medium for any and all texts humankind has sought to transmit and maintain from its inception to the current day. This exceptionally durable and adaptable medium not only aided the development of written culture throughout the world but also transformed many other human activities. From the beginning of the 14th century, particular impressions called watermarks have been inserted in European hand-produced paper as marks of recognition and quality. Watermarks are now used in different fields of study as an important support for the dating of manuscripts and printed sources lacking a precise collocation in time. Filigranology is the field of study dedicated to the research on watermarks, which, thanks to the comparison between similar marks, can help scholars reach a precise dating and implement bibliographical research on different types of sources. As asserted by John Bidwell in his essay "The Study of Paper as Evidence, Artefact, and Commodity", 'by examining paper, scholars have detected literary forgeries, discovered misleading dates in early imprints, and reassembled manuscripts in their proper order after the original sequence had been disturbed'[1].

In order to accomplish the most complete and correct dating, large quantities of data and images of watermark designs are needed. In the past, this was achieved thanks to huge catalogues of handmade tracings, gathered by luminary scholars who dedicated themselves to the exploration of numerous archives around Europe to study paper sources. Despite the important contribution of these pioneering printed repositories, which are still considered milestones in the history of filigranology, today's research can no longer completely rely on these types of sources to reach well-grounded results. The need for a standardised methodology for the study of watermarks is the main issue of the most recent research in the field. Good knowledge of the theory of paper studies is a necessary premise for solid analysis, along with an objective technique to capture images of watermarks, a standardised method for its description and a shared and open space to store the gathered information. New digital technologies, which have been introduced to watermark studies in the past years, represent an extremely helpful tool to accelerate and increase the quality and objectivity of filigranological research.

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[1] Bidwell J., "The Study of Paper as Evidence, Artefact, and Commodity", in Davison P., *The Book Encompassed. Studies in Twentieth-century Bibliography*, Cambridge University Press, Cambridge, 1992, p. 69

Generally speaking, nowadays it is difficult to find an academic who does not use digital methods as part of their study, demonstrating the profound change that research is undergoing by being mediated through technology. The digital approach to humanities has experienced different stages passing from being simply the support to the work of scholars to a genuinely intellectual endeavour with its own professional practice and an intrinsic part of numerous research projects. As explained by David Barry in his introduction to *Understanding Digital Humanities*, 'computational technology has become the very condition of possibility required in order to think about many of the questions raised in the humanities today'[2]. It is under these circumstances that digital humanities and filigranology mixed with and enriched each other. The union between the two disciplines has brought great improvements in the methodologies used for imaging, archiving and comparing watermarks, making filigranological research more reliable and open. However, great improvements still need to be implemented in the field, looking for a concrete standardisation of methods.

In this thesis, a general overview of the digital techniques used in paper studies will be described and analysed in detail, in order to underline the best practices available today for the correct registration of watermark designs. These considerations will be applied to a specific case study, the Digitisation, Recognition and Automated Clustering of Watermarks in the Music Manuscripts of Franz Schubert (DRACMarkS) project, evaluating its limitations and possible further developments.

The dissertation will be structured into three chapters, with a first theoretical introduction on paper studies and filigranology, then moving to its relationship with digital humanities, and finally concretised in the case study of the DRACMarkS project.

In particular, the first chapter will focus on handmade paper history, from its origins in China to its production in early modern Europe, passing through Arab dominions. A detailed explanation of the European way of producing paper by hand will be the focus of a further subchapter. Following, a deepened description of watermarks history and development will be outlined, in order to introduce a core topic in the dissertation: filigranology and its aid to bibliographical research. The development of this relationship and the most important resulting studies will be listed, together with an introduction on watermark description and their use for dating written and printed sources.

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[2] Berry D. M., "Introduction", in Berry D. M. (ed. by), *Understanding Digital Humanities*, Palgrave Macmillan, 2012, p. 3

After having outlined the theoretical and historical basis of filigranology studies, their concretisation and development in the digital era will be the subject of the second chapter. Specifically, the discourse will be divided into three subchapters, regarding the main aspects of the relationship between watermark analysis and digital humanities: the imaging of watermarks and paper structure using various technologies, both digital and non; the evolution in the storing of these reproductions inside printed and online collections; the latest developments in the field of image comparison and matching of watermarks.

The final focus will be dedicated to the DRACMarkS project, hosted by the Austrian Academy of Sciences at the Centre for Digital Humanities and Cultural Heritage. At this point, further analysis of specific digital methods and technologies applied in the field of filigranology will be outlined, discussing the workflow and first accomplishments of the project.

The result of the dissertation will be a complete outline of the current research context of filigranology in the digital era, supported by a deeper insight into a concrete and still in progress case study. This will help to understand the present and future of watermark research and its relationship with digital humanities, its strengths and weaknesses and its possible further developments.

1 - Paper History and Watermarks

1.1 - Paper history

1.1.1 - From China to Europe

The history of paper spans many centuries and can be divided into four periods: the ancestors; paper manufacturing in the Far East; paper making by Arabs; and European paper production. Paper as a surface for writing and drawing appeared several centuries after its discovery, and it took around fifteen centuries to spread across the civilised world.

Previously, numerous different mediums were employed as a writing surface. The first paper's ancestor is considered to be the Egyptian papyrus, made from the stalks of a reed species growing primarily along the banks of the Nile River. The fresh stalks were cut into lengths, sliced into strips, laid in two overlapping layers at right angles to each other, pressed together, and dried. Papyrus was created about 3000 BCE and exported from Egypt to other Mediterranean lands, such as Greece.

Parchment was the other writing material used before the introduction of paper, which was utilised throughout Europe until the 12th century. It was produced using animal skins, typically sheep or goat, soaked in water and lime, scraped of fat and hair and left to dry under tension. Its origin is not certain, however, Jews have used parchment rolls for copies of the Torah since ancient times. Although this writing support was much more expensive than papyrus and more difficult to produce, the raw material was easier to retrieve and resulted in a more resistant and durable final product[1].

According to the Chinese royal chronicles (*Hou Hanshu*, fifth century CE), paper was invented by Cai Lin, a Chinese court official, in 105 CE. However, archaeological and literary evidence suggests that paper had already been known for several centuries, at least from the second century BCE, and that the transmitted date was chosen somewhat arbitrarily[2]. This

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[1] Bloom, J. M., "Papermaking: The Historical Diffusion of an Ancient Technique", in Jöns H., Meusburger P., Heffernan M. (eds), *Mobilities of Knowledge. Knowledge and Space*, Vol. 10, Springer, 2017, pp. 53-54

[2] Hunter D., *Papermaking - The History and Technique of an Ancient Craft*, Dover Publications, New York, 1978, p. 50

was probably the outcome of the development of the method for creating *tapa*, a non-woven fabric that resembles felt. Furthermore, China has long been a hub for the manufacturing of silk, which was most probably of significant impact on the development of paper[3]. Paper began being used for writing in the first century CE, at least a few decades before Cai Lin supposedly invented it. Thanks to the introduction of gum as a waterproofing material, which reduced the capacity of paper to absorb ink, it became suitable for writing. Cai Lin most likely just enhanced and established the production method to make paper easier to produce, acceptable for writing, and simpler to use. He was also responsible for increasing the types of raw materials used, including recycled fibres coming from rags and ropes. In a brief period of time, paper outclassed the other writing materials and became the most widespread.

In ancient China, the process of paper making began with the maceration of raw material in water, which included raw fibres such as hemp, jute, rattan, and bamboo, as well as tiny amounts of waste material like rags and old nets. The macerated substance was then broken down and beaten until it resembled pulp. The produced pulp was then boiled with vegetal ashes. The first Chinese papermakers formed sheets using a floating fixed mould, a method which did not allow the separation of the newly formed paper from the mould until it was completely dry. This considerably slowed down the process, since the mould was not usable until it was freed from the dried pulp. The mould was generally made of bamboo or fabric and was constructed in a single piece. The process to produce paper differentiated slightly on the basis of which of the two sieves was used: when using the bamboo one, the pulp was poured on its surface and shaken to drain water; the cloth mould instead was directly dipped into the vat to float. In both cases, the felting phase occurred directly on the mould, which was left to dry outside. This resulted in long waiting times and low production. As the papermakers became more proficient and the use of paper expanded, different techniques were developed and new sources of fibre were used. In particular, papermakers began to use a different type of mould, composed of three parts, which let the mould be separated from the wood frame. This could be dipped into a vat of pulp, and let the damp sheet to be removed from the screen before drying. The new mould changed the work rhythm considerably, making it possible to start straight away with the formation of a new sheet. The newly formed paper was pressed and put to dry outside or against a stove's wall. Chinese papermakers abandoned waste fibres

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[3] Ma Y., "L'Oriente e la carta", in Cassetti Brach C. (a cura di), *Gli itinerari della carta. Dall'oriente all'occidente: produzione e conservazione*, Gangemi Editore, Roma, 2010, p. 13

as raw material and began to produce pulp from bust fibres from hemp. The qualitative characteristics of Oriental paper consisted of thickness, softness, capacity to be folded, absorbance and elevated resistance[4].

To explain the introduction of paper into Islamic culture, a legend was passed on by the Arab historian Thaalibi, in his *Book of Curious and Entertaining Information* (11th century CE). In his story, Thaalibi spoke about a battle between Arabs and Chinese that took place in 751 in Talas, where numerous Chinese prisoners were captured. Some of these were papermakers, and, after being carried to Samarkand, they were forced to teach the conquerors the rudiments of paper production. However, it is now known that paper was used and probably produced in this area of Asia decades before the battle[5]. For sure Arabs were influenced by the Chinese way of creating the paper. It is probable, however, that the contamination process was much longer than the one described in the legend.

China played a primary role in the diffusion of Buddhist scholarship throughout Asia in the first millennium of the Common Era, and Buddhism was probably also the means by which paper was spread throughout Asia[6]. Paper and paper skills were hereby exported from China to other lands, perhaps during the third century. The closer a country lay to the centres of Chinese Buddhism, the sooner paper was used and made locally. It is therefore probable that Buddhist monks brought paper making to Transoxiana (a region of Samarkand) well before the Muslim conquest[7]. The spread of knowledge was also helped by the presence of a flourishing cloth commerce along the Silk Road, connecting the Far East with Central Asia. The rapid expansion of Arabs through these territories and to the Mediterranean Sea built up a compact empire from a religious, cultural and social point of view. This compactness favoured the rapid spread of paper making techniques all over the Islamic territories, causing a transformative effect on medieval Islamic civilisation, with an extraordinary burst of creativity, from science to literature. The huge and demanding organisation of such an

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[4] Mannucci U., “Lineamenti di storia della tecnica cartaria da Ts’ai Lun a Pietro Milani”, in Castagnari G. (a cura di), *Miscellanea di storia della carta. Origini, tecniche, imprenditori, fede religiosa*, Pia Università dei Cartai, Fabriano, 1991, p. 10

[5] On the introduction of paper to Central Asia: Helman-Ważny A., “A Tale of Papermaking along the Silk Road”, in Quenzer J. B. (ed. by), *Exploring Written Artefacts: Objects, Methods, and Concepts*, de Gruyter, Berlin - Boston, 2021

[6] Bloom J. M., *Paper Before Print. The History and Impact of Paper in the Islamic World*, Yale University Press, New Heaven - London, 2001, p. 38

[7] Ibidem, p. 43

expanded Empire required a versatile and easy-to-make material for communication and storing of information, and paper was perfect for this goal[8]. Already in the 10th century CE, paper was affirmed as the most used writing support in Islamic Asia over papyrus and parchment.

The main difference between the Chinese and Arabic methods of production was the type of raw material used: in fact, raw fibres coming from semitropical plants used in Far East paper production did not grow in the arid lands of Central and West Asia. The new pulp was made mainly of linen (for whiteness) and hemp (for robustness), rags and other waste fibres, materials that were only secondary in Chinese paper production. The raw material was first immersed for several weeks in water, to remove impurities, soften fibres and make them more workable. Islamic papermakers also refined the procedure to beat macerated rags, which were, in the first period, reduced to pulp using a mortar. However, it was the introduction of another important innovative technique, the water-powered trip-hammers, that radically changed the quality and compactness of Islamic paper. As irrigation masters, the Moors were capable of using water motor power to manoeuvre complex wheel systems. The raw material was then mixed with water to create a suspension, captured and drained with the use of a flexible mould, which permitted the drying process to be carried out without the use of a sieve. The paper produced, which was rough and porous, was then sprinkled with two layers of waterproofing wheat gum, and scrupulously glazed. On Arabic paper there was also found a certain kind of proto-watermarking technique, which consisted in the practice of zigzagging the still wet newly produced sheet of paper. The main innovations introduced by Arabs in paper-making were the use of flexible moulds for manufacturing paper, the practice of employing rags as the principal raw material, pulp's refining through water-powered pestles and sizing with wheat gum.

Samarkand was the first and most important centre for paper production in Islamic Asia and remained such for several centuries. Baghdad, the capital of the Abbasid caliph, followed its example and, thanks also to the incredibly lively cultural scene, turned into another crucial paper-making site. During the 10th century CE, Damascus became fundamental for the exportation of paper to the West, which from this point spread through the Syrian region on one side and towards Egypt to the other. Paper then arrived in Tunisia and Morocco between

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[8] Riccardi M. L., "La carta araba", in Cassetti Brach C. (a cura di), *Gli itinerari della carta. Dall'oriente all'occidente: produzione e conservazione*, Gangemi Editore, Roma, 2010, p. 60

the 11th and 12th century. Fez became the reference point for paper production in North-Western Africa, and it was from this area that the techniques and knowledge for its production penetrated through Arabic Spain, where the first European paper mill was located[9].

1.1.2 - The introduction and spreading of paper production in Europe

Europeans learnt about paper making from the Arabs of Spain, North Africa, and the Levant, setting up the first paper mills in Spain in the 12th century. However, paper was already used in Europe far before that moment. Extensive diplomatic relationships between Muslims and Christians, specifically between Baghdad and Constantinople, would have made the Byzantines aware of paper much earlier. Despite this, the majority of witnesses reveal that Constantinople actually continued to import paper for a long time, not being interested in building local paper mills[10]. Iberian Christians were far more receptive to paper than in Eastern Mediterranean Europe, becoming familiar with the new medium even before the year 1000. Paper started to be produced in Spain in the early 11th century and flourished through the twelfth, specifically in the area of Valencia, mainly because of its historically flourishing plantation of linen for the production of textiles and, subsequently, of rags. Precisely, paper started to be produced in Europe in 1151, which was the year of the establishment of the first paper mill in Xativa, in the region of Valencia[11]. By the 13th century, paper was widely used for numerous practices in registry offices, monasteries, and notaries. The reason for such a rapid spread may be found in the expansion of Christian domains in the Iberian peninsula, in which Muslim inhabitants still continued to produce and practise traditional crafts, such as paper making. Without a doubt, Europeans were better at harnessing water-powered machinery than West Asians and North Africans, mainly because of the use of overshot waterwheels. Furthermore, Europe could benefit from a wetter climate and more rugged terrain, resulting in greater and more powerful water availability, providing more potential energy.

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[9] Basanoff A., *Itinerario della carta dall'Oriente all'Occidente e sua diffusione in Europa*, Edizioni il Polifolio, Milano, 1965, pp. 19-21

[10] Bloom J. M., op. cit., p. 204

[11] Basanoff A., op. cit., pp.19-21

The period in which paper came to Europe was particularly flourishing in terms of innovation. A growing interest in mechanical practices led to the restoration of old-mastered technologies, which were renowned in that period. Among these, the waterwheel, which was invented by the Romans and fine-tuned in medieval times. Their extreme receptiveness and experimental curiosity led European artisans to open up to new ideas and influences, also coming from foreign cultures[12]. The spreading of paper moved from Spain to other European territories, in particular the Italian peninsula.

By the 12th century, Italy already consumed large quantities of paper bought from North Africa and from Spain. In Sicily paper was already used in 1109. It was in Fabriano, however, that the first Italian paper mill was built in 1276, about one hundred years after the one in Xativa. The first mills were set in old neglected buildings since the limited amount of paper produced did not justify the construction of a newly constructed edifice to produce it. It did not take much time for Fabriano to become the most important centre for paper production in Europe, outclassing the Spanish paper mills in terms of quantity and quality of paper produced. This was thanks to the passage to a semi-industrial production process, in which highly specialised artisans were combined with some major technical innovations. Papermakers in Fabriano are, in fact, responsible for introducing the hammer pile, which permitted them to produce larger amounts of paper of high quality, lowering its price. Secondly, the use of animal glue for sizing was introduced: this material was more efficient than plant gelatine in waterproofing the sheet of paper while being cheaper and easier to produce. A last important innovation was the watermark, used to identify the producer, the sizing and the quality of paper. These marks were invented in order to distinguish the paper produced by a papermaker from another one of lower quality.

There is still no explanation of the reason why Fabriano became the heart of Italian and European paper production in that period. Some have tried to explain that through the previous industries present in the city, like wool production, which needed large amounts of water and watermills. Another reason may be the close contact with Arab areas through merchants or Islamic war prisoners arriving in Ancona.

After a first period of experimentation, the papermaking industry in Fabriano began its incredible expansion in the second half of the 13th century, thanks to the introduced

[12] Iannuccelli S., "L'Europa di carta", in Cassetti Brach C. (a cura di), *Gli itinerari della carta. Dall'oriente all'occidente: produzione e conservazione*, Gangemi Editore, Roma, 2010, p. 97

innovations. The economic development was principally due to the entrepreneurs' capacity to grasp the perfect occasion for paper manufacturing development. Another important economic class which certainly had a role in Fabrianese industrial development was merchants, taking advantage of a system which was starting to move away from the medieval corporate regime. The quality of the paper and the improvement of techniques led to a higher level of production, increasing the prestige of Fabrianese papermakers. The paper produced in Fabriano started to be known outside its region and outside Italy as a superior product when compared to the paper imported from the Arabs. The efficiency with which European papermakers made their products available allowed them to dominate the market, not only in Italy but also throughout the Mediterranean. This uncontested hegemony led to the rapid decline of Arab papermaking. The city merchants expanded their investment in the paper production sector, creating direct relationships with papermakers: by doing so, the merchants commissioned and secured a part of the production. This made artisans strictly dependent on the requests made by retailers, for which they were paid a fixed salary or at piece rates. This salary position pushed the papermakers to look for other places to grow their own business[13].
The increasing competition inside Fabriano territories, the hegemony of merchants in the city's paper market and production, and the continuously growing request for paper: these were probably the causes of the diaspora of Fabrianese papermakers started in the 14th century. The artisans moved to other cities in Italy, like Bologna, Padova and Treviso, and to territories beyond the Alps. Here they were recruited by foreign merchants, establishing the first paper mill in Nuremberg, Germany, at the end of the 14th century[14]. This phenomenon caused the development of new centres for paper production around Europe and the standardisation of the methodologies and equipment. The production of paper moved to other European territories, like Spain (substituting Arab production), France, the Netherlands, Belgium, Switzerland, and England. From the 15th century onwards, paper production could be found all over Europe.

The invention of printing in 1453 by Gutenberg was another important boost for paper production, particularly in Germany; it was in this period that a number of paper mills opened in the southern part of the German territory, together with the first printing presses. The

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[13] Iannuccelli S., op. cit., p. 100

[14] Castagnari G., "La diaspora dei cartai fabrianesi. Un'indagine aperta", in Castagnari G., *L'impiego delle tecniche e dell'opera dei cartai fabrianesi in Italia e in Europa*, Cartiere Miliani Fabriano, Fabriano, 2007, p. 27

spread of paper in some areas was directly dependent on the invention and diffusion of printing. This caused the division of Europe into two separate groups: the Western one, in which paper production arrived before print, and the Eastern one, in which paper mills were introduced after the first established printing works[15]. It has to be said that if paper production had not been so developed and active in the period of printing's invention, it would have been much more difficult for this new technology to spread. The availability of paper in large quantities allowed the production of books on a previously unknown scale. This caused the development of an early form of vertical integration, which brought together printers and paper makers. Gutenberg's invention resulted in a growing need for a much cheaper paper, manufactured not for writing but specifically for printing, with a softer, not-so-hard-sized surface. In the 16th century, the technology of making printing paper started to become separated from the technology used in manufacturing writing paper. The retail trade was conducted by notaries and booksellers, but also by pharmacists, selling related products such as sealing wax and ink.

Until the second half of the 18th century, practically no changes occurred to the way paper was produced, except for the introduction of the Hollander beater. This was invented in 1650 as an alternative to the stamping mill developed in the early modern years: the new invention permitted the maceration of rags using less power than a traditional beater and made the process faster and more effective. The competition between producers was very high: smaller paper mills, even though concentrating on a more local horizon, displayed a certain amount of aggressiveness; substantial papermakers competed feverishly for foreign and luxury markets.

By the end of the 18th century, some paper mills developed to be important, highly capitalised, labour-intensive concerns, with operations carefully documented in ledgers, correspondence, judicial records, and census data[16]. The research for new types of raw materials, the beginning of industrial production and the invention of the papermaking machine led, in the first period of the 19th century, to the complete transformation of the paper making sector[17]. The first important progress in the production of paper was made thanks to the use of chlorine as an additive to pulp, invented by Karl Wilhem Scheele in 1774. This innovation helped the

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[15] Basanoff A., op. cit., pp. 19-21

[16] ilab.org/fr/article/the-study-of-paper-as-evidence-artefact-and-commodity, Bidwell J., " The Study of Paper as Evidence, Artefact, and Commodity", Online version, Antiquarian Booksellers' Association of America, 21 December 2009. Last visited 28/09/2023

[17] Gaskell P., *A New Introduction to Bibliography*, at the Clarendon Press, Oxford, 1972, pp. 214-223

process of bleaching, widening the possibility of using not only pure white rags but also coloured and second-quality clothes. The fundamental innovation brought to the production of paper was the papermaking machine, introduced by Nicholas-Louis Robert in 1798 and further implemented by the Fourdrinier brothers. The introduction of this machinery set off the beginning of the industrial period of papermaking production: not only were no more skilled operators required, but also the productivity, even with the earliest prototypes, was much more substantial compared to hand-papermaking mills. Finally, the other huge problem of handmade paper was related to the availability of raw materials: in fact, in the first period of production using the papermaking machine, the demand for rags was outstripping the supply. The research for a substitute, cheaper and more abundant raw material had begun already in the second half of the 18th century. However, rags were successfully and completely substituted only in the second half of the 19th century. After all these types of innovations, handmade papermaking remained something related only to extremely fine paper types.

1.1.3 - The European method to produce handmade paper

As said before, paper was produced in the same way in practically all of Europe from the 13th to 19th century, apart from the introduction of the Hollander in the 17th. In fact, as affirmed by Leonard N. Rosenband, 'a painter or engraver from Luther's day would have found much that was familiar in the paper mills of Rousseau's'[18]. The method, originally derived from the Chinese and the Arab one, was primarily based on the way of producing paper used in Fabriano at the beginning of the 14th century.

Hand papermaking was a capital-intensive industry, unusually dependent on the synchronised labour of skilled craftspeople. Two fundamental raw materials were at the basis of paper production: water and rags. Water has been a fundamental source for the production of paper since its invention in China. This had to be as clean and pure as possible, free of debris and specks, and had to flow fast, in order to maintain the movement of the watermill. Furthermore, papermakers might have noted the ill effects of water high in iron content,

[18] Rosenband L. N., *Papermaking in Eighteenth-Century France. Management, Labor, and Revolution at the Montgolfier Mill 1760-1805*, The Johns Hopkins University Press, Baltimore - London, 2000, p. 8

which causes a reddish or brownish cast[19]. Water often bedevilled Europe's papermakers, since the need for a strong flow of clean water, with a proper balance of trace elements, to drive mill-wheels and to produce white paper was not that easy to find. The other fundamental material for the production of early European paper was rags. In the warm and humid regions of China where paper was invented, papermakers made their product principally from bast fibres collected directly from semi-tropical plants and shrubs. This could equally be made from the cellulose in linen and cotton rags, old ropes, and other textile waste, a process that was adopted in the harsher and drier climates of Central Asia, where it was used not only by the Buddhists, who had introduced paper to the region, but also by local merchants and bureaucrats. At that time, papermakers apparently discovered (or rediscovered) that paper could have been produced using rags and waste textiles made from such plants as cotton, flax, and hemp. In addition, they actually understood that paper was much easier to produce when using fibres that had already been processed and bleached. Arabs consequently learnt to make paper from both bast fibres and rags, and this mixture was on the basis of the early paper produced in Samarkand. As described in the article by A. F. Rudolf Hoernle:

> Gradually, as the raw fibre, especially that of the mulberry tree, gave out, they [the Arabs] increased the substitution of rag fibres; and as they must have soon discovered that this substitution answered very well, they finally ended by limiting themselves entirely to the use of woven or worked-up fibres, contained in rags, ropes, nets, and such like material, mostly linen, which could be obtained by them in large quantities.[20]

For this reason, European paper, directly derived from the Muslim method of production, used rags as the main raw material until the late 18th century.

Since the production of paper was part of the so-called "mechanical arts", the skills required and the fundamental phases of the process were normally handed down orally. For this reason, no descriptions of the early modern methods of producing paper were transmitted. The first texts were published in the 18th century, describing the late modern process. Undoubtedly, the two most influential works in this sense are the *Art de faire le papier* by Jêrome de Lalande, and the explanatory tables contained in the *Encyclopédie* by Denis Diderot and Jean

[19] paper.lib.uiowa.edu, Barrett T., *European Papermaking Techniques 1300-1800*. Last visited 15/06/2023

[20] Hoernle A. F. R., "Who Was the Inventor of Rag-Paper?", *The Journal of the Royal Asiatic Society of Great Britain and Ireland*, Cambridge University Press, Oct. 1903, p. 673

d'Alembert. It is thus risky to assume that the methodologies used to produce paper in 1700 are similar to the earliest ones, also because of the scarcity of direct archaeological material (such as sieves, moulds and other tools used in the process) at our disposal. However, the analysis of paper sheets conserved in archives and libraries and produced at the earliest dates of European papermaking helps to hypothesise the way in which earlier paper mills worked.

The production of paper starts with the retrieval of linen rags, frequently in short supply and quite difficult to find. Rags were in fact collected by a specific figure, the *straccivendolo* (Rag collector), who sold them to the paper mill. He was often the owner of a small store in which he selected and divided rags on the basis of their colour and their quality: whites were the finest and were sold to paper mills authorised to produce refined paper; black rags were instead used by specific paper mills specialised in the production of packing material or general secondary paper.

Arrived at the paper mill, the rags were divided on the basis of their grade of thickness, in order for similar rags to be beaten together. Mixing rags of different types together would force the crews to prolong the stamping and to add water to the pulp, risking its ruin. That is why it was fundamental to start with a good selection of similar rags in terms of weight, colour and softness. These rags were then washed for the first time to remove dirt. Their quality was checked another time to divide the most well-conserved rags from those worn out.

The clothes were then put to macerate for several weeks on the basis of their quality: high-quality linen normally took more time to break down than coarse, and linen that had been worn required more time than new[21]. The process of fermentation (also called retting) was the job of a specialist in well-established mills, and a crucial step in paper production, preparatory to the transformation into pulp. The macerated rags were cut into smaller pieces and sometimes washed again before being brought to the stamping room.

The stamping mills consisted of rows of great wooden hammers, also called pestles, which were made to rise and fall by means of a series of cams on a stout axis, beating the rags while water flowed through troughs underneath, called vat-holes. The general setup is based on multiple troughs, each fitted with multiple hammers faced with tackle intended to accomplish a specific job: the first set in the first trough was shod with rather aggressive heads designed to break the fibres into smaller bits; after being well cut, the rags were manually moved into

[21] Hunter D., op. cit, p. 154

the second trough, were the hammers were fitted with rounded nails, designed to separate the remaining bits of cloth into individual cellulose fibres; the third type of hammers were faced only with plain wood with the purpose of brushing, liquefying the pulp. As beating progressed in the breaking and beating troughs, the fibre was constantly washed with fresh water for two major reasons: to lighten the colour of the finished paper and to clean the fibre of impurities and microbes[22].

The Hollander beater, a Dutch invention introduced at the end of the 17th century, was designed to replace water-powered stampers with wind-powered ones, to consume less energy and to increase production. The new beater was made of a single oblong wooden tub fitted with a partition that ran along the centre of its length. The rags circulated in this tub and were lacerated by the action of metal bars on a roll which revolved over a bed plate set on the bottom of the tub. The cloths circulated continuously around the tub as the bar-to-bar shearing action cut the rags into smaller pieces, the smaller pieces into individual threads, and the threads into fibres. Even though the production using the Hollander beater seemed to be more effective in terms of resources used and control over the quality of the final product, the debate about which of the two methods was the better was quite lively. In fact, it was thought that fibres produced by modern stampers remained longer and therefore of higher quality. This caused numerous mills in France, Germany and Italy to continue producing paper using old methods, sometimes supporting the process with a couple of Hollanders.

After the fundamental phase of beating, the resulting pulp was diluted in a vat with water at a specific percentage on the basis of the paper that had to be produced. The man responsible for the decision of how much pulp to put in water was the vatman. The vat was then filled up with water and pulp suspension. Later in the 17th century, it was also heated in order to make the pulp drain more rapidly, to make it more fluid and homogeneous, and to make the process more comfortable for the vatman. The other instrument at the basis of sheet formation was the mould, fitted with an open wooden frame called a deckle, determining the size of the paper. This apparatus was strung with two sets of wires, thick chain lines that ran from the top of the mould to its bottom and supported the fine, and perpendicular narrow laid lines. The group of people involved in this part of the process was made of three operators: the vatman, the coucher and the layman. Lalande tells how, after having dipped the mould into water and suspension and having risen it horizontally above the water's surface, the vatman:

[22] paper.lib.uiowa.edu, Barrett T., op. cit.

> spreads the stuff on the mould by gently shaking from right to left and from left to right, as if he wished to riddle it, until it is spread equally over the whole surface of the mould; this is known as ‘promener’: or to ‘shake'. In the same way, by another movement which is made by pushing the mould forward and pulling it back in a to and fro motion, as if riddling, the stuff binds and knits together and becomes perfect; this is known as ‘serrer’ or to ‘shut’ the sheet. […] Immediately this stuff, so fluid, which seems no more than slightly cloudy water, knits together […] In this way the sheet precipitates onto the brass screen while the water drains away through the interstices and a real sheet of paper remains on the mould.[23]

When all the water has poured out, the vatman removes the deckle fitting it directly into the second empty mould and the formation of another sheet starts again. The occupied mould is passed to the coucher, who is responsible for rotating the sheet of paper rapidly upside down by pressing it onto a damp woollen felt, transferring the sheet of paper onto a felt surface. The coucher then passed the newly empty mould to the vatman and laid a new layer of felt on the freshly made sheet of paper, in order to avoid contact between still wet sheets[24]. This process was repeated six or seven times a minute (about 4250 per day) until the pile of felts, each

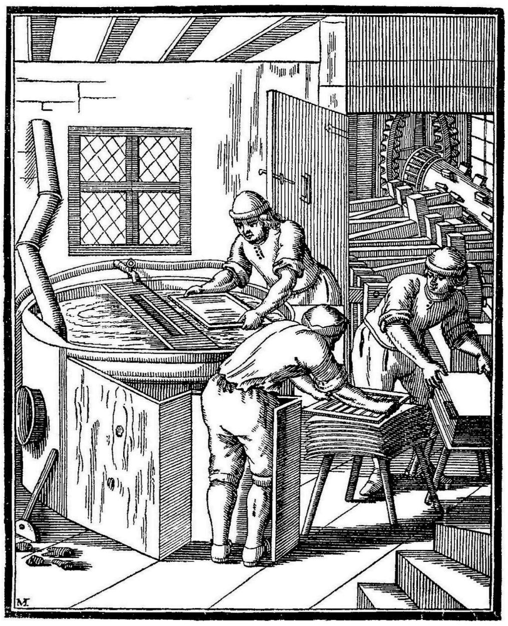

Fig. 1 - Making paper by hand in Europe of the 17th century as presented by Elias Porcelius

[23] Lalande J. J. L. (de), “Art de faire le papier”, in *Description des arts et métiers*, Vol. 4, Académie royale des sciences, Paris, 1761. Translated by MacIntyre Atkinson R., *The Art of Papermaking*, Kilmurry, Ashling Press, Ireland, 1976, p. 37

[24] Iannuccelli S., op. cit., p. 136

bearing a sheet of paper, reached a customary height of 160 to 420 sheets[25]. The coucher and the vatman worked in tandem. As the vatman slid one mould onto his comrade, its twin, shorn of its fresh sheet, was on its way back to him (Fig. 1). Their labour, rich in routine and considered choices, was exhausting. At some mills, vatmen and couchers commonly switched jobs during the day to ease the strain on backs and shoulders.

The paper and felt pile, called post, was placed in a press and the three operators stopped their work and moved to help with the pressing. This process was the first to start the expulsion of excess water from the freshly made paper. It was also fundamental for the work of the layman, who was then responsible for separating felts from paper and placing sheets on a new pile. A careless layman could cause a great deal of damage, which is why Lalande considered this role ‘suitable only for people who had practised it from an early age and not for uneducated, inexperienced country folks’[26]. At this moment, the pile of paper was again subject to pressure, in smaller presses and with much less power. They were then separated again and put into a new post that was pressed again. This process went on until the perfect smoothness of the sheet surfaces was reached.

After the phase of pressing, paper was brought to the drying rooms. Here the sheets of paper were hung by the wives and daughters of the operators over the ropes made of cow or horse hair in groups of seven or eight, called spurs. This drying method left the paper smooth and free from excessive curling, as opposed to sheet-by-sheet drying[27]. Fundamental in this phase of the process was the ventilation system in the drying room, possible thanks to a series of windows positioned in a way that sheets would dry slowly and evenly.

After two or three days, the sheets were collected by the sizerman and a new final part of the process began: the sizing of paper sheets, another important step in paper production. Sizing was fundamental for filling paper pores so that it would become impervious to ink, especially when speaking of writing paper, and much more durable and long-lasting. The gelatine size was made from pieces of animals, generally sheep, directly obtained from a butcher or a tanner. The small cutouts from animal skin were washed and boiled for several hours. A number of sheets were held together and dipped in the warm glutinous liquid, then extracted

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[25] Pedemonte E., Vicini S., Princi E., “Storia della produzione della carta. Dalle lavorazioni artigianali cinesi dei primi secoli d.C. alle manifatture industriali inglesi del XIX secolo”, in Pedemonte E. (a cura di), *La carta. Storia, produzione, degrado, restauro*, Marsilio Editori, Venezia, 2008, p. 34

[26] Lalande J. J. L. (de), op. cit., p. 41

[27] Hunter D., op. cit., p. 186

and squeezed in a press. The sized sheets were then moved again in the drying room and held singly, to prevent them from being glued together.

Finally, paper sheets were brought to the last step of production, which is the glazing, also called pinching. This part of the process, as described by Lalande, consisted of 'the finisher passing a smooth agate stone, with considerable pressure, over both sides of the paper, almost always pushing the stone forwards'[28]. In this way, the paper surface became much smoother and looked better.

Female hands were finally responsible for sorting paper by weight, measurement and appearance, removing blemishes when possible, and tying the reams. This was then lent to the merchants responsible for the distribution of paper locally and supra-nationally.

1.2 - Watermarks

Charles-Moïse Briquet, in his introduction to *Les Filigranes*[29], describes four categories of characteristics lent by the mould on the sheet of paper, the first three intrinsic to its construction:

I. The paper format - this refers to the dimension of the paper, and it is determined by the mould used to produce the sheet. Paper formats have varied in time and location during the evolution of papermaking around Europe. In the public square of Bologna, Italy, a carved stone was displayed showing the four allowed formats of paper in that period. This was the first kind of document which certified the dimensions of paper sheets in early modern Europe. Some of these formats remained in use later in paper history;
II. The laid lines - formed by brass strands, are responsible for the holding of paper pulp. They are positioned close to each other in order to drip water and hold the fibres;
III. The chain lines - supporting the laid lines, are normally separated by a few centimetres. This measure is a fundamental point of research on paper;
IV. Watermarks - the impression left by a metal strand decoration secured to the mould structure, and have to be considered as the most important characteristic of hand-made

[28] Lalande J. J. L., op. cit., p. 52

[29] Briquet C. M., *Les Filigranes. Dictionnaire Historique Des Marques Du Papier Dès Leur Apparition Vers 1282 Jisqu'en 1600*, Genève 1907, Leipzig 1923, I, pp. 2-4

paper. Differentiating from the other types of impressions, it is instead intended to make the final product recognisable, and it has no specific structural purpose[30].

Sometimes "watermark", as defined in the *Dictionary and Encyclopædia of Paper and Paper-making* by Emile Joseph Labarre, is 'the term used to indicate the lighter lines or makings in paper, more especially visible when the sheet is held up to the light, caused by the wires on which paper is made, […] or their production and, by analogy, the metal design from which the impression is made'[31]. However, in this work a more specific definition is used as given by Karl Theodor Weiß, who describes watermarks as:

> light-coloured marks in the paper which are generally only visible when viewed against light and which serve as marks of origin and business or as marks for the craftsman identification, as marks of quality and size or as protection against abuse, but also for the protection of the paper.[32]

This definition concentrates more on their primary functions rather than on their appearance. These marks thus have multiple functions and usefulness both from the point of view of the producer, the consumer and the regulator: the papermaker was able to distinguish his product from that of other paper mills; consumers could distinguish between different kinds and qualities of paper on the basis of their needs; the authorities used watermarks to regulate paper market and trade. Not all paper was watermarked, but most medium-quality paper and nearly all the finest ones had watermarks of some sort[33].

Watermarks are then a proper fingerprint for paper, a unique, unmistakable and unchangeable characteristic of each individual sheet[34]. For this reason, they have proven to be an extremely

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[30] Harris N., *Paper and Watermarks as Bibliographical Evidence*, Institut d'Historie du Livre, Lyon, 2017, p. 32

[31] Labarre E. J., *Dictionary and Encyclopædia of Paper and Paper-making*, Swtes & Zeitlinger, Amsterdam, 1952

[32] 'nur bei Gegenlichtbetrachtung erkennenbaren hellingen Gebidlde im Papier, die als Herkunfts- und Geschäftszeichen oder Mestermarken, als Kennzeichen von Sorte und Format oder auch zum Schutz gegen Mißbrauch, seltern zum Schumck des Papiers dienen'. Weiss K. T., *Handbuch der Wasserzeichenkunde*, bearbeitet und herausgegeben von Wisso Weiss, Fachbuchverlag, Leipzig, 1962, p. 1. Translation by the author

[33] Gaskell P., op. cit. , p. 61

[34] Tschudin P. F., *La carta. Storia, materiali, tecniche*, trad. it. Sacchi E., Edizioni di Storia e Letteratura, Roma-Passariano, 2012 (ed. orig. *Grundzüge der Papiergeschichte*, Hiersmann, Liepzig, 2002), p. 39

useful tool for various scholarly disciplines, among all bibliography. The in-depth study of these signs, in fact, helps scholars to collocate undated manuscripts into a specific time frame, also giving information on the geographical area of production. All these analyses concern filigranology, the subject often considered to be an ancillary discipline of paper studies, bibliography and more in general of history, responsible for the inspection, description and cataloguing of watermarks.

In the next subchapters, an introductory history of watermarks useful for understanding its origins and developments will be found, followed by a preliminary explanation of the uses and application of filigranology in bibliographical studies. A further deepened analysis of watermark description and dating will be outlined in order to give a first glimpse into the study of paper as a useful tool for manuscript positioning in time and space.

1.2.1 - Watermarks history

Even though some kinds of marks were already present in early Islamic paper, watermarks are undoubtedly a product of late medieval European culture.

The structure of the mould in the Chinese papermaking process, made of bamboo, did not allow the application of any kind of sewed design to form a watermark. However, decorative watermarks have also been found in paper produced in Asia, made of leather, hydrophobic cardboard or fabric fixed to the mould. These types of marks were quite rare and there is no instance of them in any Islamic paper.

Some other kinds of impressions were instead visible in paper produced in medieval North African and Spanish territories. These are normally referred to as *zig-zag* marks and were seemingly made by a sort of comb, called *mastara*, while the freshly made sheet was still resting on the mould. Numerous questions still arise from these kinds of signs: several scholars have tried to infer at which stage of production, how and why these impressions were made, trying to guess if the zig-zag marks may be considered a kind of watermark ancestor[35].

[35] On the zig-zag sign in Arab paper: Estève J. L., "Le zigzag dans les papiers arabes. Essai d'explication", *Gazette du livre médiéval*, No. 38, 2001, pp. 40-49; Le Léannec-Bavavéas M. T., "Zigzag et filigrane sont-ils incompatibles? Enquête dans les manuscrits de la Bibliothèque nationale de France", in *Le papier au Moyen Âge: histoire et techniques*, édité par Monique Zerdoun Bat-Yehouda, Turnhout, Brepols, 1999, pp. 119-133; Schulte U., "Einige Bemerkungen zu den Zick-Zack-Linien in frühspanischen Papieren", *Papiergeschichte*, Vol. 12, 1962, pp. 7- 9

Some scholars, among them Heather Murphy, suggest that these kinds of signs were ‘used to thin the paper where it was to be folded in order to reduce “swelling” in the spines of books when the papers were bound’[36].

The evolution of the mould into a metallic structure in medieval Europe opened up the possibility of inserting papermarks into sheet production. The first European watermarks originated in central Italy around the end of the 13th century. The date of the first watermark is still quite uncertain today, as is the name and precise location of the first paper mill to have invented it. The oldest watermark ever found may be a sign of a Greek cross contained in a sheet of paper dated 1282 and preserved in the city archive of Bologna, as described by Briquet[37]. However, there is no certainty in this statement, as explained by Neil Harris in his work *Paper and Watermarks as a Bibliographical Evidence*, since the paper in question is not referenced exactly by Briquet and thus has never been found again in Bologna’s archive[38]. Some other scholars have reported an even earlier watermark revealed in a paper from Cremona dated 1271. Considering that this sign, a letter “F”, is very similar to other watermarks traced by Briquet and dated to the first half of the 14th century, the Cremona watermark is almost certainly of a later date.

The first signs were presumably created for paper production insiders, like papermakers and merchants, to make it easier to distinguish one quality of paper from another, or for consumers to differentiate paper coming from one mill or another. Their design was initially quite elementary, consisting of simple lines or symbols, formed by thick metal wires attached to the mould[39]. Fabriano was a thriving centre for the production of wool, and in the first period the work of papermakers was strictly related to that of wool producers: the first paper mills in the city, in fact, were supposedly set in disused *gualchiere*, buildings in which woollen cloths were made. This makes it probable that the two professions and their work were strictly linked, and probably that is the reason why some early watermarks are similar to signs found in records of wool guilds. In the first period of watermark production at the beginning of the 14th century, many names of papermakers were used as paper signs, to

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[36] https://www.qdl.qa/en/imagery-early-watermarks, Murphy H., *The Imagery of Early Watermarks*, 28 September 2021. Last visited 20/06/2023

[37] Briquet M. C., *Les Filigranes…*, cit., I, p. 10

[38] Harris N., *Paper and Watermarks…*, cit., p. 47

[39] Beadle C., “Development of watermarking in hand-made and machine-made paper”, *Journal of the Society of Arts*, London, Vol. 54, May. 18 1906, p. 690

identify the producer and suggest the idea of a kind of production mark. These fell into disuse quite quickly, as suggested by Briquet[40], because of the small number of literates capable to read and recognise written names. Therefore, papermakers decided to resort to diffused and well-known signs, in order to make it easier for people to recognise their product.

With the evolution of papermaking, the art of watermarking also improved and opened up to new designs: the need for the identification of paper was vastly supported by an aesthetic aspect, with thinner wires and more complex designs. The spread of paper and watermarking techniques around Europe evolved into innumerable different kinds of marks, relating both to quality, sizing (from the 16th century) and origin of paper. These signs represented human figures, animals, and plants, but also single letters or entire names or words, numbers, objects of various kinds, heraldic emblems, geometric shapes or religious symbols. In Troyes, 1406, Charles VI was the first to declare that paper mills couldn't use the watermark of another producer, and to that point, some signs were officially conceded to single paper mills.

In areas of high concentration of paper mills and with the evolution of the newly formed territorial states, the diffusion of signs relating to a specific geographic area and recalling national or regional heraldry was a common practice. Starting between the 16th and 17th century, single paper mills added initials or other symbols as private trademarks, in the first period together with the main mark, and then as an additional mark, called countermark, on the other half of the sheet. The mark did not identify the papermaker in itself, rather the paper mill, as the characteristics of the final product were, in fact, the responsibility of numerous workers employed in the paper mill, and not only of a single artisan. Paper was also affected by the quality of raw materials, like rags and water, and was thus important for the potential consumer to know the region and place of origin of the sheet. Another type of watermark called corner mark, originated in Northern Italy, positioning a smaller sign on the side of the sheet opposite to the main mark, in one of the corners. There is no actual evidence about how different paper mills chose their symbols: they could have been transferred or inherited from the previous mill owner, could have remained practically unvaried for centuries or changed at every proprietary transfer with personal symbols.

Labarre affirms that watermarks did not, by themselves, enhance the quality of paper: they were, as a rule, used only on the better qualities of writing and printing paper and are

[40] Briquet C. M., *Les Filigranes*…, cit., I, p. 10

therefore popularly supposed to be a guarantee of quality[41]. It is now known, however, starting from the 17th century, that some marks did in fact describe the quality of paper, differentiating medium or poor quality sheets from finer materials.

As the art of papermaking spread around Europe, the meaning of symbols, formats, and watermarks evolved and changed on the basis of each papermaking location. As Philip Gaskell explains in his *A New Introduction to Bibliography*, the position of the marks on the mould also changed considerably over time: in the first period of papermaking, watermarks were placed almost anywhere on the mould surface: 'by the fifteenth century they were normally put in the centre of one half of the oblong so that when a sheet of paper was folded in half the watermark appeared in the centre of one of the two leaves'[42].

A significant invention in the history of paper which affected the art of watermarking was the introduction of wove paper by James Whatmans around 1756: this type of paper eradicated the irregularities caused by the chain and laid lines, using a paper mould with brass wires woven together, creating a mesh. This new design made paper with a smoother surface, similar to ancient parchment. For this reason, its name in French is *papier vélin*, deriving from the Latin word *vellum*, which means fur, or leather. Watermarks continued to be used also after the introduction of wove paper, which enhanced the shapes of marks, no longer hidden by laid or chain lines. In the first period, the wire watermark was positioned on the wove mould in the same way as it was in the production of laid paper. At the beginning of the 19th century, some experiments were made to create a type of "filled" watermark, in which letters and signs were no longer characterised by thin profiles, but were heavy, cut from metal sheets and fixed on a woven sieve, generating filled-in, light-shaded watermarks[43]. At about the same time, dark and light-and-shade watermarks were invented; this technique permitted a chiaroscuro figure, where the fibres in the paper ran from thin to thick, producing an image with many shades from light to dark. This was formed thanks to a specific technique which consisted of the woven wire being pressed so that, as explained by Durd Hunter, 'the stock, or pulp, was held in two degrees of density or thickness, which formed backgrounds for the

[41] Labarre E. J., op. cit.

[42] Gaskell P., op. cit., p. 61

[43] Rückert P., Hodeček S., Wenger E. (eds.), *Bull's Head and Mermaid, The History of Paper and Watermarks from the Middle Ages to the Modern Period*, Stuttgart - Vienna, 2009, p. 21

outline single wire portraits or emblems'[44]. The technique then developed into more complex forms, completely transforming the art of watermarking and making it possible to produce all sorts of images in chiaroscuro.
The first types of paper produced using the papermaking machine were unwatermarked, due to the fact that it was not possible to attach any kind of wire to the Fourdrinier-invented machine. When a new type of papermaking machine was invented by Josef Braham, working with cylinders instead of moving woven mesh, it was possible to apply watermarks on the cylinders, so that the signs were produced together with the formation of the paper sheet. Later a way was also invented to impress watermarks on the damp paper produced by the Fourdrinier machine[45].
Watermarks are nowadays still used in numerous paper-related fields, as an anti-forgery measure and as a sign of quality.

1.2.2 - Watermarks and paper as bibliographical evidence

Bibliographical research and paper studies are strictly connected to each other and watermarks are at the basis of this relationship. The characteristics of papermarks and the way in which they are produced make it possible to use them as a fundamental tool for bibliographical studies: the comparison of watermarks and other signs left during paper production (like chain and laid lines) can help establish the date and place in which a sheet was made. This is possible, however, only when significant features of the watermark are recognised and recorded. The main objective of filigranology is to determine general empirical rules for the observation of single cases.
The awareness of the importance of watermarks and paper studies to bibliography has grown over time. The use of watermarks as bibliographical evidence began to arouse scholars' curiosity from the middle of the 19th century, when interest in cultural studies was generally rising. One of the first catalogues approaching the study of watermarks to specify the date and origin of a woodcut book was Sotheby's *Principia typographica* in 1858. Already by 1859, in

[44] Hunter D., op. cit., p. 295

[45] Weiss K. T., op. cit., pp. 296-297

his article *Notes pour server à l'historic du papier*, Vallet-Virville pointed out the usefulness of watermarks as a tool for bibliographical investigation:

> The studied watermarks, carefully compared, must tell us, after a sufficiently through investigation, and in a more or less punctual way, what is the age and antiquity of a watermarked sheet; they must also tell us the place where a paper was manufactured… It is therefore a question of drawing up an exact register of marks used by the papermakers in various places and at various times.[46]

The willingness to build catalogues of watermarks concerning signs of specific periods and geographical areas as a useful tool for bibliographical research had begun to arise.
Concerning research on Italian watermarks, the work by Augusto Zonghi and his brother Aurelio in Fabriano laid the foundation of filigranlogy studies in Italy. As an archivist and librarian, Augusto became interested in watermarks, indexing hundreds of documents in order to illustrate the history of paper and to make a contribution to paleographic studies. In the second half of the 19th century, the Zonghi brothers were considered among the major experts of filigranology in Italy. Even if the work of these two eminent scholars was only the beginning of a much deeper knowledge of watermarks, their consciousness of the importance of the identification of the watermark, the analysis of laid and chain lines, the comparison between two documents containing the same watermark, the research on the place of origin and production, and the studying of commercial routes, are all elements considered to be essential also in today's bibliographical research.
The first major international catalogue of watermarks and one of the most important works in filigranology history is the result of Briquet's research, with the publication of his volume *Les Filigranes. Dictionnaire Historique Des Marques Du Papier*, at the beginning of the 20th century. Initially, the research was meant to concentrate only on Swiss watermarks, as described by the author in the first pages of his volume[47], in order to compare these signs with other already collected medieval ones. As the research evolved, Briquet started to understand

[46] "Les filigranes étudiés, comparés avec soin, doivent nous dire, après une enquête suffisamment approfondie, et d'une façon plus ou moins précise ou ponctuelle, quel est l'âge et l'antiquité d'une feuille marquée de tel ou tel filigrane; ils doivent nous apprendre aussi quel est le lieu où un papier a été fabriqué… Il s'agit donc de dresser un registre exact des marques employées par les papetiers en divers lieux et en divers temps". Vallet-Virvillet A., "Notes pour server à l'historic du papier", *Gazette des Beaux-Arts*, Vol. II, 1859, p. 230. Translation by the author

[47] Briquet C. M., *Les Filigranes*…, cit., I, p. XI

the importance of watermarks as a fundamental instrument for fixing the date of a document. The decision was then made to focus not only on the Swiss territory, but to travel also to other European countries, including Italy, France, Germany, and Austria to retrieve information about ancient paper mills and locations. The result of his work was a repository containing 44,000 tracings of watermarks, which permitted him to identify the majority of watermark designs, or at least, by analogy to similar signs, to identify approximately the period and area of origin.

The other important international catalogue of watermarks is contained in the work by the German scholar Gerhard Piccard, in the series of the seventeen *Findbücher* published between 1964 to 1997, containing 92,000 reproductions of tracings. The method used is the same as Briquet, covering most of the handmade papermaking period in Europe. The geographical area included in this study is more circumscribed, and some decisions about the layout and size of tracings have been questioned by some scholars, affecting the final quality of the work. However, the *Findbücher* remain among the most influential catalogues of watermark tracings, an important tool for bibliographical research.

A fundamental milestone in bibliographical research on watermarks was the realisation in the '50s by the scholar Allan Stevenson of one crucial fact about signs in paper: watermarks are twins[48]. Stevenson is for this and other important statements responsible for codifying 'the scholarly study of paper as bibliographical evidence'[49], and thus must be included among the most influential scholars in paper studies.

As underlined by Karl Theodor Weiss in his *Handbuch der Wasserzeichenkunde*, 'Filigranology must first be able to give a clear and objective description of watermarks… They must be described methodically in order to register and catalogue them'[50]. There are numerous advantages in choosing watermarks and paper as evidence for bibliographical research, as several are also the aspects to take into consideration for a productive and grounded bibliographical study based on paper analysis.

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48 Stevenson A. H., "Watermarks Are Twins", *Studies in Bibliography*, Vol. 4, 1951, pp. 57-91

49 Needham P., "Allan H. Stevenson and the Bibliographical Uses of Paper", *Studies in Bibliography*, Vol. 47, 1994, p. 24

50 "Die Wassezeichenkunde muß also erst einmal eine klare eindeutige Beschreibung der Wasserzeichen geben können…Sie müssen methodisch beschreiben werden, um sie überhaupt verzeichnen und katalogisieren zu können". Weiss K. T. , op. cit, p. 7. Translation by the author

1.2.3 - The bibliographical description of watermarks and paper

A fundamental assumption to have in mind when looking at paper and watermarks is the one pointed out by Stevenson in his studies, which is that watermarks are twins. Though historians of paper had noticed the fact of companion moulds, not much attention has been paid to the pair of watermarks produced by such moulds. It is well known that, during the formation of paper at the vat, two moulds were used, in order to make the work of vatman and coucher more fluid. While the first was dipping a mould into the vat to collect fibre suspension and form the paper sheet, the second was laying the other mould on the felts' post, to detach the just formed sheet from the sieve. After having finished their work, the two operators exchanged the moulds, so that the vatman had a new empty sieve to fill up with paper fibres, and the coucher had a newly formed sheet to detach from the sieve onto felts. These two moulds are the subject of Stevenson's research: in fact, the two sieves were meant to be identical, both structurally (laid and chain lines) and aesthetically (watermark). This opens up the possibility of two similar signs coming from the same post. Not two paper moulds were ever precisely identical, however. Even two moulds of a pair, which were deliberately made to look alike, can be told apart by the paper made in them. Often the differences between the moulds of a pair are gross and obvious, but if not, tiny details might be noticed anyway[51]. This is because mouldmakers, specialists in the making of sieves for paper production, were major experts in forging identical moulds meant to work simultaneously on the same vat. However, as explained by Stevenson:

> Even when a skilled artisan took special pains with moulds for fine paper (as sometimes he did), the complexity of the design, differences in chains and lettering, and wear of the wireforms in use prevented one watermark from being or continuing to be a replica of the other …With good sight, undiffused light, and a millimeter scale, the bibliographer today can train himself to distinguish the watermarks from companion moulds, except where heavy print or close binding serve to defeat him.[52]

These pairings of moulds revealed to be a precious tool for bibliographical research. A paper stock can only be defined once all the copies of moulds have been identified, allowing for

[51] Gaskell P., op. cit., p. 62

[52] Stevenson A. H., "Watermarks are twins", cit., p. 65

much more reliable dating of paper. The absence of twin signs annotation is considered one of the fallacies of Briquet's work, since he was aware of the fact while collecting watermarks but did not systematically report it in his repository. He gave a simple and not concrete definition of the differences between *filigranes identiques*, *filigranes similaires* and *filigranes divergentes*[53], which however is not sufficiently satisfying for a correct comparison and match of mould-mates watermarks. In fact, he identifies as *filigranes identiques* not only those watermarks produced by the same wire but also those signs coming from twin moulds, which are, for the majority of the time, not identical at all[54].

In his article commenting on the works by Stevenson, Paul Needham outlines his own descriptive system to approach the study of paper and watermarks and uses them as bibliographical tool[55]. This method will be followed here to approach the complicated topic of bibliographical paper description, a long process requiring the highest attention and precision.

Before looking specifically at the marks inside paper, it is good practice to determine the original size of the sheet. This might be of a certain difficulty in some cases, especially for bound printed books in which paper was normally shaved and folded several times, forming different sizes: the folio, which is the larger format consisting of a single folded sheet; the quarto, created by folding paper twice; the octavo, when paper is folded three times, forming eight single leaves. These formats specifically refer to the way in which paper was folded rather than to a precise measure of the single page. Knowing the original size also helps to collocate the fragment of watermark inside the sheet and, in some cases, to reconstruct its original appearance by looking for missing parts.

The second fundamental point for a consistent description of paper sources is to describe and measure precisely the number and distance between chain lines and the density of wirelines, the insertion of interpolated chain lines to support the watermark (typical of Italian paper), and the pattern of tranchefiles, used to reinforce the narrow ends of the mould and thus helpful to figure which originally was the sheet's short edge. This is a crude but clear method to give a first description of paper's characteristics.

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[53] Briquet C. M., *Les Filigranes*…, cit., I, p. XIX

[54] Stevenson A. H., "Paper as a Bibliographical Evidence", *The Library*, Fifth Series, Vol. XVII, N. 3, 1962, p. 201

[55] Needham P., op. cit., pp. 31-33

After these first assumptions, the bibliographic description moves on with the identification and localisation of watermarks, if present. Stevenson describes a consistent and unambiguous structure for illustrating and analysing a couple of sheets presumably coming from the same mould. From Stevenson's studies, one of the first things to have in mind while looking at handmade paper is to recognise and distinguish the so-called *felt side* from the *mould side*: in paper that has not been vigorously polished, it is possible to distinguish clearly, on the sheet side which laid directly in contact with the mould, the pattern of both chain and wire indentations, while the other side (the felt side) is more or less flat, or shows wire humps only[56]. These indentations help the bibliographer to orientate the paper sheet and are considered to be 'among the simplest and most reliable forms of bibliographical evidence'[57]. This not only helps to identify whether the watermarks are positioned on the left or right side of the mould, but it also assures that the comparison between sheets is always performed from the same side[58].

There is no unique interpretation about which side should be the one to look at while describing and indexing watermarks. Stevenson suggested to look at paper from the "right side", which means from the mould side, since he interpreted the idea of looking at the watermark as it was printed from the mould on the sheet of paper. Other scholars, like Harris, suggest instead to look at paper from the felt side, since it was both the way in which the vatman sow it when forming the sheet of paper and also how the watermark was depicted on the original mould. The English version n. 2.1.1 2013 of IPH standards suggests 'to collect data with the wire side facing down'[59]. However, since there is no actual standard on how to look at and register paper, the suggestion has always been to at least specify which of the two sides of the sheet it was observed from, and to use that side consistently throughout the study.

The way in which the paper scholar is looking at the sheet is fundamental in order to describe the position and orientation of the watermark in the page. Ideally, for a bibliographically consistent description, a mark must be localised on the sheet to its right or left side. In order to

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56 Gaskell P., op. cit., pp. 60-61

57 Stevenson A. H., "Chain-Indentations in Paper as Evidence", *Studies in Bibliography*, Vol. 6, 1954, p. 182

58 ihl.enssib.fr, Harris N., "Paper Studies", in *Analytical bibliography. An alternative prospectus*, Institut D'Historie Du Livre, 2004. Last visited 27/09/2023

59 International Association of Paper Historians, *International Standard for the Registration of Papers With or Without Watermarks*, Version 2.1.1, 2013, p. 4, para. 3.0.19

define the position of a watermark, it is first necessary to identify its orientation and look at it from its upright position. This is defined by Weiss as the *Schaulage*[60] which, for the vast majority of marks, is self-evident. However, not all watermarks have an obvious orientation, like symmetrical forms of circles and moons, so that the decision from which side to look must be taken arbitrarily. Not having a precise orientation does not permit the identification of a precise right or left side of the sheet. For an even more specific type of localisation of the marks, it is necessary to take note of the chain spaces that separate the watermark from the nearest short edge of the sheet. This makes it easy, with a short description (e.g. the one used by Needham[61], mR3 = mark in the right half of the sheet, third chain-space in), to define the position of the sign and to compare it with a possible twin watermark. Other types of measurements useful for the identification of a watermark are its height and width, and the average distance between the laid lines.

Countermarks, which were typically opposed to the main mark and centred on the other sheet half, have to be recorded too. In large and medium-sized formats (folios and quartos) the countermark usefully indicates that the other half of the sheet still comes from the same mould. These marks also fall outside the printed area of the leaf, so that are much more easily visible. It is also crucial to notice and index the presence of cornermarks in a sheet: this is a characteristic quite underestimated by past bibliographers, who normally did not notice or failed to index these signs in the correct way. Their presence is fundamental to outline since they are a sign typical of some specific geographic areas (Northern Italy), so they are useful to identify the origin of some sheets.

After having noted all this preliminary information, it is time for the scholar to address the actual description of the watermark motif. This has been done in numerous different ways in the past century, concentrating more on the significance of the watermark rather than on its current representation. The methodology proposed for the analysis and description of paper and watermarks is based on the IPH standards. In order to make watermark and paper bibliographical research consistent and effective in 2013, the IPH, International Association of Paper Historians set a list of standards. These are fundamental for the right compilation of the metadata associated with each single watermark representation, which otherwise would not have been significant for comparison with other watermarks. Images lacking extra

[60] Weiss K. T., op. cit., p. 86

[61] Needham P., op. cit., p.32

information are, in fact, useless, as are the reproductions not correctly recorded. The more detailed the information about the paper sheet is, the more valuable it is for comparison with similar sheets. It goes without saying that only information that can be assessed with certainty has to be recorded, in order to minimise inaccuracy.

In order to avoid misunderstandings, the IPH has set a series of steps to correctly outline the watermark using a verbal description[62]:

- The main mark present in the paper determines its allocation to the main class;
- Further markings and variants are noted in a subsequent subclass;
- Watermarks incorporating several components are documented by noting the primary element code first, followed by the additional element codes, separated by hyphens, regardless of their sequence or location in the mark;
- Suffixes and extra digits can be used to code components of a whole (for example, “head”, “bust”, or “fruit”), as well as location and heraldic specifics.

This type of description does not take into account any indication of form or meaning but supports the outline based on the presentation of the watermark, avoiding terms which are not object-related. The list of watermark main classes is presented in the First Appendix. A standardised description of paper and watermarks helps to avoid ambiguities. However, there are cases in which it becomes particularly difficult to recognise the design of a watermark and what it is actually supposed to represent. This is because of the lack of iconographic knowledge, or simply because the cultural reference of some watermarks has lost its meaning over time and it is no longer decipherable[63].

Apart from the actual identification of watermark design, IPH standards state other information related to the source that has to be noted too. This consists of its place of storage, the institution that is responsible for its conservation, the manuscript or collection signature, and the specific paper sheet containing the watermark; if known, the author of the manuscript and the place of use; for printed works, the author, place and year of publication. In addition to that, when registering a digitally produced watermark image, the type of reproduction technology has to be noted. The different types of technologies used for the imaging of watermarks and paper structure will be discussed further in Chapter 2.1.

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62 International Association of Paper Historians, op. cit., p. 10, para. 5

63 Limbeck S., “Wozu sammeln wir Wasserzeichen? Vom Nutzen eines Papiermerkmals für Editoren”, in Schubert M. (hrsg.), *Materialität in der Editionswissenschaft*, De Gruyter, Berlin, 2010, p. 34

1.2.4 - The dating of watermarks and paper

After having looked at how to register paper sheets as evidence for bibliographical research, there are some crucial aspects to have in mind when using watermarks and paper as tools for dating manuscripts and printed sources. Before starting, it has always to be kept clearly in mind that the correlation between the date and place in which a sheet was made and those in which it was used is never a safe assumption. For this reason, numerous precautions have to be considered before inferring the actual dating. A list of these will be the object of the following subchapter.

Peter F. Tschudin[64] distinguishes three levels of dating reliability: the first and most certain is contemporary dating, based on the paper directly dated by its consumer, merchant or producer at the time of its use. This forms a reference point for further chronological research on other sources; the handed-down dating, based on the owner's annotations, date of use or any other fact bearing a date which is related to the issued paper; the last type is the inferred dating, in which the chronological collocation of the source is only based on assumptions and hypothesis generated thanks to comparison with other paper sheets of certain dating.

It is at this last level that watermarks and paper studies help the historiographers and bibliographers to place a sheet of paper chronologically, or at least to reduce the time frame in which this paper might have been produced and used. Watermark dating accuracy must be based on matching sheets of paper generated by the same mould. As explained by Kitty Nicholson in her article "Making Watermarks Meaningful: Significant Details in Recording and Identifying Watermarks", in order to be considered identical two watermarks must have identical size and shape, 'identical details, identical countermarks, as well as the same recognizable sewing dots and the same laid line frequency (number of lines per cm) and the same chain line interval (cm between lines)'[65]. Apart from the exact matching of the two watermarks, in order to correctly date a source, some aspects of the paper production and selling workflow have to be taken into consideration.

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64 Tschudin P. F., "The Mould: its Function, History and Important in Historiography", in Castagnari G. (a cura di), *La forma. Formisti e cartai nella storia della carta occidentale*, Fondazione Istocarta, Fabriano, 2015, pp. 130-131

65 Nicholson K., "Making Watermarks Meaningful: Significant Details in Recording and Identifying Watermarks", in The American Institute for Conservation, *The Book and Paper Group Annual*, Vol. 1, 1982

The first fundamental element of this analysis is the mould, how it was produced and how it was used. The mould is the principal tool for the formation of paper and is also one of the most important instruments for bibliographical analysis. Mouldmakers, specialised workers among the most highly prised and paid in the industry, worked independently and wandered from mill to mill, repairing old moulds and wiring new ones. When one of these was worn out, it was replaced by another mould, which was never absolutely identical to the previous one; it would have differed in the wires, in the number and the distances between the chain lines, in the shape and the size of the watermark or in the placing of the same on the sieve. Moulds were subject to severe wear which resulted in noticeable deterioration of the mould surface: wires of the sieve were gradually bent or broken, watermarks were distorted and lost elements of design. Traditionally, most filigranologists and scholars, among them Briquet, Stevenson and Theo Gerardy[66], agree on the fact that a mould of a common paper size was ruined and discarded in about two years. However, a papermaker did not produce always the same type of paper, the number of moulds available to him were several and of different types. For example, the moulds for the creation of sheets of larger formats were used less and lasted much longer than the most common sheet-size moulds. These variables tend to increase the possible years of use from two to around four. In his article "Last Words on Watermarks"[67], Curt Bühler points out various discrepancies in the assertions of other scholars regarding the lasting and use of the paper mould: in fact, he doubts that the moulds were used only for four years, and supported the idea of a much longer lifespan of ten years or even more.

By comparing the impressions left by the mould on different sheets, it is possible to collect a group of papers that presumably originated from the same or twin moulds. If there are among these one or more dated sheets, it is possible to confirm that the other undated ones of the same group are around the same age and thus were probably used in the same period. A good way to determine a chronological order among the paper sheets coming from the same mould is the study of mould deterioration. Due to its hard and continuous use, the mould was subject to great changes during its lifetime, with wires of the sieve gradually bent or broken, and

66 Gerardy T., "Der Identitatsbeweis bei der Wasserzeichendatierung", *Archiv für Geschichte des Buchwesens*, Vol. 9, 1968, p. 734

67 Bühler C. F., "Last Words on Watermarks", *The Papers of the Bibliographical Society of America*, Vol. 67, No. 1, 1973, pp. 1-16

watermark wire distorted and losing elements[68]. The changes occurring on the mould surface are a further indication and a helpful tool for dating a sheet of paper: it is possible to reconstruct the related chronology thanks to the comparison of mould deterioration resulting in paper structure, in which the watermark moves away from its original position (Fig. 2). This deterioration is both caused by the frequent mould use and by its cleaning using a brush. Repairs made to the mould are easily visible in the final sheet and are also useful to better locate the paper sheet in time.

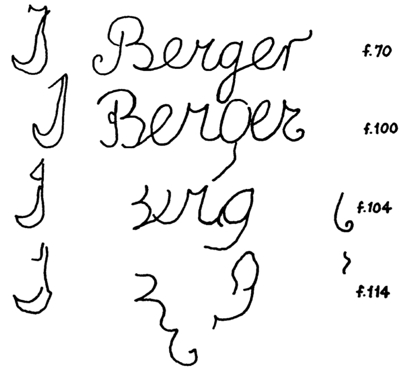

Fig. 2 - Watermark deterioration in MS of Paer's *Olinde et Sophronie* (1824), US-Wc

After having assumed the dating of the mould that produced a specific piece of paper, another factor that has to be taken into consideration while trying to date a manuscript or printed book is the time passing between the production of paper and its actual use. It was, for the majority of the cases, very improbable that any paper consumer bought and stored large quantities of paper to be used at some later time. This is because paper, independently from the historical period, was considered a luxury good, and thus affordable only in small quantities at each purchase. Paper was therefore bought only when truly needed, and consumed in a short period of time. In the majority of the printed books between the 15th and 18th centuries, there are typically found just one or a few types of paper throughout the entire source. This demonstrates that the paper was purchased specifically for the manufacturing of that book, and most likely not long after its fabrication. Finding one or few types of watermarks in the same source has been explained by Stevenson as the "Runs and Remnants" Principle[69]: in the

[68] Tschudin P., "The Mould: its Function, History and Important in Historiography", cit., p. 132

[69] Stevenson A. H., *Observations on Paper as Evidence*, The University of Kansas Libraries, Lawrence, 1961, pp. 19-24

cases in which a small amount of paper types is present inside a source, the printing of that book happened not much after the production of the paper itself. In fact, for reasons of cost, printers tended to calculate the amount of paper necessary for each job extremely accurately and order an exact needed quantity from their supplier, in order to avoid large quantities of paper deposited in the warehouse[70]. As a consequence, the random appearance of a specific watermark in a book may signify some remnant of stock used for an earlier book and maybe unnoticed in the printer's warehouse for years.

Handwritten sources are considered a bit differently: as already said, paper was an expensive good, meaning that any normal consumer would have bought just a few sheets of paper every time on the basis of his own need, explaining the great mixtures of the paper present inside some manuscripts. Also, merchants who were responsible for carrying paper through national and over national territories obtained supplies from a number of single makers, mixing and selling different types of sheets of the same quality together[71]. All these considerations helped scholars, such as Theo Gerardy and Gerard Piccard, to assert that the time passing between the formation and usage of a sheet of paper was of a few years, around four.

However, one must not forget that paper has been an international commodity from the very beginning of its history, commercialised from one region to another along arduous routes, crossing several borders before reaching its intended market. As underlined by John Bidwell in his work "The Study of Paper as Evidence, Artefact and Commodity", the presence of imported paper from other countries varied 'depending on tariff barriers, the cost of transportation, the cost of manufacture at home and abroad, and the ability of domestic mills to satisfy local demand at competitive prices'[72]. The transportation of goods would have taken a long time in past conditions, so that the timespan between the production of the paper and its selling to the final user depended also on the distance between the paper mill of origin and its final place of use. The task of determining the actual paper mill that was responsible for producing the paper sheet at issue is, for the majority of the cases, difficult to accomplish. In fact, the geographical positioning of paper mills, their name, the distance between the various places of production and places of use, the duties, and the cost of transportation are all factors

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70 Ridolfi R., *Le filigrane dei paleotipi*, Olschiki, Firenze, 1957, pp. 13-14

71 Labarre E. J., op. cit

72 ilab.org/fr/article/the-study-of-paper-as-evidence-artefact-and-commodity, Bidwell J., "The Study of Paper as Evidence, Artefact, and Commodity", op. cit.. Last visited 28/09/2023

and information to have in mind while trying to deduce the origin of a paper sheet. The watermark, which also can be used as a sign of origin, may be misleading if not inspected carefully. In fact, the moulds and watermark wires could have been exchanged between papermakers or, in other cases, subject to plagiarism between one paper mill and another. The attribution of a watermark to a specific paper mill has to be based on in-depth research on its trademark or emblem and on the identity of its owner, confirmed by documents and concrete evidence. This is only possible after having developed a list of names considering paper mills and papermakers as complete as possible. In the latest examples of handmade paper produced from the late 15th and first 19th centuries, the countermark would normally display the name of the paper mill opposed to its emblem. This, of course, simplifies the attribution of the paper sheet to a specific place of origin. There are several catalogues of watermarks attempting to retrace their place and paper mill of origin. A well-known example is curated by Georg Eineder and edited by Emile J. Labarre, entitled *The Ancient Papermills of the Former Austro-Hungarian Empire and their Watermarks*[73]. Eineder was able to reconstruct a summary of each region with a list of the paper mills present in each individual territory, together with their specific watermarks.

[73] Eineder G., *The Ancient Papermills of the Former Austro-Hungarian Empire and their Watermarks*, Paper Publications Society, Hilversum, 1960

2 - The application of digital humanities to paper studies and filigranology

Having underlined the importance of watermarks for bibliographical research and the characteristics to have in mind while looking at paper sources, the necessity for tools to trace, compare and store these marks comes into question. In the past, the recognition and reproduction of watermark images was done by hand, using tracings and collecting the results in huge paper repositories. In recent decades, numerous and different have been the novelties and progress in watermark research thanks to the introduction of digital methods. Technology is greatly revolutionising filigranology, leading to new important discoveries and opening up to hitherto unknown paths. It is here that the relationship between digital humanities and paper studies comes into play.

In this chapter, the evolution of digital methods for the study of paper and watermarks will be discussed. These include reproduction techniques and their evolution in time, the storing of this information in physical and digital repositories, and the techniques for comparison and further analysis of watermarks and paper as dating tools.

2.1 - Watermarks reproduction

The first step to take when approaching the study of watermarks is their inspection and reproduction. Compared to verbal descriptions, full-scale illustrations yield one important practical advantage: the pictures circumvent technical terminology's language and translation problems. That is why watermark images are a central tool in bibliographical studies, used for comparison between sources and for further research when the original material is not accessible for inspection. Reproductions also help to enhance watermarks and paper shapes, giving the scholar a better view of their characteristics, which normally might be obscured by writing or lost in the binding of a book.

Watermark reproductions, once inaccurate and hand-made, are now executed with digital methods, which have increasingly improved their reliability and readability. Looking for a substitute for hand-made tracings and rubbing, in the mid-20th century bibliographers started to inspect non-destructive and more accurate techniques for paper structure reproduction. As the research developed, different approaches were considered, each of them investigating paper via a different type of electromagnetic radiation imaging system. Specifically, beyond the range of visible light, technologies making use of infrared, ultraviolet and X-ray wavelengths were considered for their different proprieties useful for paper inspection. In recent years, the development of these methods in a digital form is giving hope for the evolution of various fields of research, higher accuracy of reproductions and faster and easier ways of sharing, comparing and storing the results.

Before actually beginning to reproduce the design of a watermark, some fundamental steps have to be kept in mind. These are crucial for consistent and effective research, both for comparison with other studies and for filogranological reasons.

The first step is to acknowledge and differentiate the sieve and felt side of the sheet. This is useful, as previously asserted, in order to consistently represent watermarks throughout the manuscript or print source from the same leaf side. After this, a first visual inspection and orientation of the watermark is performed, in which the observer takes note of the general characteristics of the watermark, its representation and meaning. It is also important to check the presence of possible countermarks or corner-marks, which are normally located in the inferior section of the sheet. The presence of this specific type of watermarks has to be registered too. Ideally, the best watermark images are one-to-one size, also taking care of reproducing paper structure. All this information helps scholars with further research and easy comparison with other images. However, the capturing of the entire watermark in a single picture is not always possible, for example, because of its location in the binding of the book or manuscript.

In the next sections, a general overview of the different techniques used for paper and watermark imaging is given[1].

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[1] For a general overview on reproduction methods for paper and watermarks: Meinlschmidt P., Märgner V., "Advantages and Disadvantages of Various Techniques for the Visualization of Watermarks", *Restaurator*, 2009, No. 30, pp. 222-243; Hiary H., "Watermark reproduction techniques and existing related works", in *Paper-based Watermark Extraction with Image Processing*, University of Leeds, Leeds, 2008, pp. 18-23; Schoonver D., "Techniques of Reproducing Watermarks: A Practical Introduction", in Spector S. (edited by), *Essays in Paper Analysis*, Folger Shakespeare Library, Washington - London, 1986, pp. 154-164; Schreiner M., Wallner-Holle H., "Determination of Watermarks by Non- Destructive Techniques. Comparative Studies", in Graziaplena R. (edited by), *Paper as a Medium of Cultural Heritage, Archaeology and Convervation. 26th Congress - Association of Paper Historians*, Istituto centrale per la patologia del libro, Roma, 2004, pp. 142-151; Müller E., "Describing and Representing Watermarks. From Paper Catalogues to Online Databases", in Hufnagel S., Sigurðardóttir Þ., Ólafsson D. (eds.), *Paper Stories – Paper and Book History in Early Modern Europe*, De Gruyter, Berlin - Boston, 2023, pp. 111-142

2.1.1 - Freehand drawing, manual tracing and rubbing

The first and most rudimental attempts for the reproduction of watermarks were carried out by simple freehand drawing and copying of the watermark's design. These kinds of drawings, reproduced by means of woodblocks or copperplates, gave only a rough idea of what the original sign would have looked like. The engravings and printing of reproduced watermarks did not consider the other fundamental characteristics of the paper sheet, like laid and chain line references, and are therefore inadequate for bibliographical research.

In the early 19th century, the most used method in filigranology was manual tracing. Some of the major paper scholars and pioneers of the subject, among them Briquet, Piccard, Haewood, Zonghi and numerous others, made use of this method for their research and creation of watermark catalogues. This extremely simple but somehow efficient technique basically consisted of positioning the leaf at issue onto a light table, or against a near a window, in order that the watermark was clearly visible, putting a blank paper onto the surface and tracing the profile of the sign with a soft pencil, normally with hardness between 2B and HB. Briquet wisely suggested tracing, along with the watermarks, the chain lines on either side and noting the wirelines[2]. In this way, it was also possible to take note of other crucial information about the sheet and maintain the tracing of the same size as the original impression, making it easier to recognise identical or twin marks. However, the limitations of this method are quite evident: tracing watermarks through another sheet of paper reduces visibility, and the result of tracing will not in any way be sufficiently precise to be used as bibliographical evidence. In fact, it is really difficult, even for the most skilled and experienced tracers, to record also minor details, like sewing dots or other minor differences in watermark outline. The absence of these characteristics, which are crucial for identifying plausible mould twins, makes hand-traced watermark collections useful as general guides for the first recognition of marks' representation and meaning. However, this reproduction technique still results in being not sufficient for further bibliographical studies. The IPH standards suggest reproduction via tracing only when other methods like rubbing, UV photography or radiography are not allowed or are judged impractical or dangerous for the

[2] Briquet C. M., *Les Filigranes…*, cit., I, pp. XVII-XVIII

source. In this particular instance, the use of a protective film, such as KODATRACE, is strongly recommended.

A third manual method for the reproduction of watermarks and paper elements is rubbing, also called *frottis.* This technique consisted of placing the watermarked leaf with the sieve side facing up onto a hard surface, positioning the clean copy paper on top. Using an unsharpened soft lead pencil, from upper left to bottom right, diagonal strokes are created in close proximity throughout the full surface of the watermark. A softly tinted black area is obtained, revealing an exact duplicate of the mark in its original size[3]. Rubbing is considered to be an easy and quick technique, not requiring any special equipment and, from the point of view of conservationism, safer than tracing. However, the results are still considered not optimal, since surface irregularities are also traced and appear as lighter or darker regions in the final reproduction. This technique has been primarily discarded for conservation reasons, since frottis can still have some kind of effect on the original source, such as scratching or flattening.

These methods, though considered to be obsolete and inaccurate by today's research standards, actually have the advantage of not covering the image of the watermark with the overlying printed or written text. This allows scholars to at least have an initial idea of how the watermark is, where it is positioned in the sheet, and what is the density of laid and chain lines.

2.1.2 - Photographic methods and back-lit images

Photography has been another widespread method used from the early 20th century for reproductions of watermarks, one of the first no-contact techniques used in filigranology studies. There are various photographic techniques used in paper recording. The most basic one starts with positioning the leaf in front of a homogeneous light source and taking a picture of the retro-illuminated sheet. The sheet might be protected on either side by a plexiglass slab. The watermark will then be visible and recorded in its entirety. Some preventative measures

[3] International Association of Paper Historians, *International Standard for the Registration of Papers With or Without Watermarks*, p. 8, para. 4.4

must be taken, as suggested by Richard Field[4], like the right calculation of exposure depending on paper thickness, and the maintenance of lens distance. In this way, every image of a watermark bears the same relationship to the original as every other, preserving the same scale.

The greatest advantage of this method is its ease of use and the inexpensive material needed for its obtaining, making the study and investigation of watermarks easier for individual scholars. However, a major limitation is revealed immediately when looking at the just-taken image: if the paper surface is covered with writing or printing, it is practically impossible to record any particular from the leaf structure. That is why it is normally preferred when using photography to select blank sheets or clean areas to have a better visual of the watermark. It is not enough, however, just to rely on the presence of empty pages or blank areas in a source in order to reach a high-quality research result. There are only a small number of works relying on these simplest photographic techniques, and even in these cases, it was not always possible to retrieve perfect images of all the marks.

The availability of digital photography, modern computers and advanced image processing tools permitted research programs at the beginning of the 21st century to improve the photographic technique applied to watermark studies. The major achievements have been the algorithms and systems capable of isolating watermarks and laid and chain lines from the rest of the elements on paper. The foundation of this method, digital image processing and manipulation, is a cornerstone of the improvement of back-lit imaging systems. Image processing includes noise reduction, contrast and brightness enhancement via histograms, image sharpening, frequency filtering[5], segmentation, object recognition, morphological operations[6], edge detection[7], image analysis, etc. Examples of these methods applied to

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[4] Field R. S., "On Photographing Watermarks", *The Print Collector's Newspaper*, Vol. 8, No. 3, 1977, p. 75

[5] Frequency filters process an image in the frequency domain. The image is Fourier transformed, multiplied with the filter function and then re-transformed into the spatial domain. Attenuating high frequencies results in a smoother image in the spatial domain, and abating low frequencies enhances the edges.

[6] For mathematical morphological operation is intended a set of image-processing operations based on shapes. Morphological operations apply a structuring element to an input image, creating an output image of the same size. In a morphological operation, the value of each pixel in the output image is based on a comparison of the corresponding pixel in the input image with its neighbours. These are primarily used to remove imperfections. The morphological top-hat transform is used to remove non-uniform image backgrounds.

[7] Edge detection is the operation capable of detecting discontinuity in brightness to identify edges and curves in a digital image. It is used for image segmentation and data extraction.

watermarks studies are Piero Zamperoni's research[8], where back-lightened images and manipulation via morphological closing, top-hat transform and frequency filtering are used; Paul Whelan et al.[9], also used morphological top-hat transform for the estimate and removal of background, morphological reconstruction to clean remaining noise, and used Discrete Fourier transform to remove laid lines[10]; Di Jin[11] studies using image enhancement techniques like transmitted image contrast and edge detection to extract watermarks; also the older project by the firm Fotoscientifica "La marca d'acqua", described in the article by Daniela Moschini, made use of ultra-high definition camera, producing 'files consistent enough to undergo high magnification without distortion'[12]. The simplest and most straightforward approach for manipulating back-lit images of watermarks is the use of Adobe Photoshop. Working on contrast and separating the background from the main image of the watermark helps, in a few simple steps, to enhance the visibility of the inner structure of paper[13].

A considerable problem, however, for many of these research programs remained interference and noise of overlying writing or images, even after manipulation. This is because heavy writing and printing are difficult characteristics to remove just by using a manipulation approach to a back-lit photograph. It is here that image subtraction comes into play: as explained in *Paper-based Watermark Extraction with Image Processing* by Hazem Hiary, this consists of the difference between two images, A and B, 'denoted as $D(x, y) = A(x, y) - B(x, y)$, where x and y are the coordinates of pixels pairs in images A and B'[14]. Image A consists of the reflected photographs of the front or back of the paper sheet, while the B picture is the

8 Zamperoni P., "Wasserzeichenextraktion aus digitalisierten Bildern mit Methoden der digitalen Bildsignalverarbeitung", *Das Papier*, Vol. 43, No. 4, 1989, pp. 133-143

9 Whelan P. F., Soille P., Drimbarean A., "Real-time registration of paper watermarks", *Real-Time Imaging*, Vol. 7, No. 4, 2001, pp. 367-380

10 Laid lines cause a peak in frequency domain due to their high density in the paper sheet structure.

11 Jin D., *Paper and watermark digitization and analysis*, Master's thesis, School of Computing, University of Leeds, 2004

12 Moschini M., "La Marca d'Acqua: A System for the Digital Recording of Watermarks", in Mosser D. W. et al. (eds.), *Puzzles in paper: Concepts in historical watermarks*, Oak Knoll Press and The British Library, London, 2000, p. 188

13 For a description of research programs using Photoshop: Bradley L., "The use of digital imaging to record watermarks", *AICCM Symposium 2006 Conservation of Paper, Books and Photographic Materials*, Wellington, New Zealand, 2006, pp. 137-146; Valero C., "Tip: Enhancing Watermark Images: A Photoshop Method", *The Book and Paper Group Annual*, No. 37, 2018, pp. 178-190; Edge D., "The Digital Imaging of Watermarks", *Computing in Musicology*, No. 12, 2001, pp. 261-274

14 Hiary H., *Paper-based Watermark Extraction with Image Processing*, University of Leeds, Leeds, 2008, p. 29

back-lit image, enhancing watermarks and internal leaf structure. The process basically passes through recto removal, backlit-verso registration, verso removal, image grouping (arithmetic mean) and final watermark location. In this way, Hiary successfully aligned the front and back sides of the manuscript to attempt minimising, as much as possible, unwanted interference that obstructs the watermark patterns caused by recto and verso writings[15].

In most recent years, the research by Pablo Ruiz et al.[16], William A. Sethares, Margaret Holben Ellis and C. Richard Johnson[17] and Elisa Ou et al.[18] have pointed out some major advances in the techniques for back-lit imaging and watermark enhancement. Ruiz, together with other scholars, introduced a method similar to the one proposed by Hiary, however based on a different algorithmic principle: the technique is instead based on a multiplicative model for attenuation produced by paper when crossed by light, rather than a subtractive model as in the previous research. The results reached by Ruiz are satisfying and resemble the outcomes of radiographic methods (described in Chapter 2.1.4). Furthermore, the fully automatic algorithm does not need any image processing expertise to operate and it is rapid and accessible to individuals and to institutions with little cost or specialised equipment. The research project carried out by Sethares on Leonardo's *Codex Leicester* is basically similar to the one implemented by Ruiz, differing in the use of a linear model, which allows for numerical optimisation when combining the three images of recto, verso and transmitted light. The computational watermark enhancement procedure will be part of a package distributed under an open-source licence, including basic calculations and features to facilitate its use by researchers with Photoshop-level skills. Finally, the project proposed by Ou et al. developed the Watermark Imaging System (WImSy), a system for the extraction of watermarks combining surface image removal and alignment of multiple transmitted light images via

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[15] Other works by Hiary, developing the technique of recto and verso removal: Boyle R. D., Hiary H., "Watermark location via back-lighting and recto removal", *IJDAR*, No. 12, 2009, pp. 33-46; Said J., Hiary H., "Watermark location via back-lighting modelling and verso registration", *Multimed Tools Appl*, No. 75, 2016, pp. 5673–5688; Hiary H., Ng K., "Automated Paper-based Watermark Extraction and Processing", *Proceedings of the Second International Conference on Automated Production of Cross Media Content for Multi-Channel Distribution (AXMEDIS'06)*, 2006

[16] Ruiz P., et al., "Visible transmission imaging of watermarks by suppression of occluding text or drawings", *Digital Applications in Archaeology and Cultural Heritage*, Vol. 15, 2019

[17] Sethares W. A., Holben Ellis M., Johnson C. R., "Computational Watermark Enhancement in Leonardo's Codex Leicester", *Journal of the American Institute for Conservation*, Vol. 59, No. 2, 2020, pp. 87-96

[18] Ou E. et al., "The Watermark Imaging System: Revealing the Internal Structure of Historical Papers", *Heritage*, No. 6, 2023, pp. 5093-5106

High Dynamic Range (HDR) photographs. By first combining a series of back-lit images with different exposure times using HDR and then de-noising the resulting image, the group of scholars was able to achieve a high quality watermark image.

The latest digitally transmitted light imaging techniques are considered among the best methods for watermark reproduction. The major limitation has always been the difficulty in extracting the mark outline, an operation that had to consider the removal of interference and noise caused by overlying writing or printing, the possibility of uneven background illumination and damaged paper. In the most recent period, the improvement of image manipulation processes and the superior quality of final photographs has led to a notable step forward in the technique, resulting in watermark reproductions similar to the ones obtained by radiographic techniques. Furthermore, the equipment needed to retrieve back-lit images of paper is inexpensive and thus affordable by most small cultural institutions or single scholars. Back-lit images remain one of the quickest, simplest and cheapest ways of reproducing watermarks.

2.1.3 - Photosensitive methods

Photosensitive methods have been another alternative for watermark reproduction, using the way light passes through the sheet of paper and hits a photosensitive film underneath.

Phosphorescence watermark imaging makes use of ultraviolet light shined onto a plate covered with a photosensitive pigment. A method of this type was described by Carol A. Small in her article "Phosphorescence Watermark Imaging", in which a combination of ultraviolet and infrared light are used for watermark enhancement. As explained by the author:

> Infrared waves cancel the effects of UV waves on the light-emitting proprieties of phosphorescent pigment embedded in a plate. UV waves will excite the pigment plate to phosphorescence overall. When watermarked paper is placed on the plate, IR waves will penetrate the paper both in areas of standard thickness, as well in thinner areas that comprise the watermark, laid lines, and chain lines, causing the phosphorescent pigment to go dark.[19]

[19] Small C. A., "Phosphorescence Watermark Imaging", in Mosser D. W. et al. (eds.), *Puzzles in paper…*, cit., p. 169

The combination of these two types of wavelengths causes the glowing of phosphorescence pigment only beneath the thinner part of the paper sheet, so underneath watermarks and laid and chain lines. A photograph can then be made to record the final appearance of the plate. The result is a one-to-one reproduction of paper's inner characteristics, obtained rapidly, safely and at very low costs. This technique is perfect for quick reproductions of watermarks, or for their simple identification. However, some limitations are present, since the produced images can't be considered of the higher quality. This is because ink, still visible in the near-infrared spectrum (780-2500 nm), affects the reproduction of the watermark, superimposing onto its image. Also, in order to obtain a clear image, the ratio of UV and IR waves penetrating paper must be high. Anything which reduces the ratio reduces image quality, such as the thickness of paper, absorption of light by the paper, and the absence of good contact between the source and the phosphorescent plate. This method had no particular appeal to filigranology studies, mainly because of the high limitations in the quality of watermark reproduction.

Another similar technique is Dylux, developed in the early 1960s, which is an Instant Access Imaging Paper, photosensitive to UV light, popular for watermark representation until the early 2000s. The American scholar Thomas Gravell[20] was the first to use this technique for filigranology studies, firstly on stamps, then enlarging his research to all types of watermarked paper. The procedure to obtain a reproduction of a watermark using this technique is quick and simple: the special paper is placed behind the watermark and exposed to a source of visible light, which passes more readily through the thin areas of the paper structure. Subsequently, Dylux paper is exposed to UV radiation, with the less exposed part turning to a deep blue colour, while the coating turns white in correspondence to the thinner areas of the paper sheet structure. The time of exposure depends on the thickness of the paper and varies between 5 to 20 minutes. The result is a superimposed image of the watermark and internal structure of paper, revealing also the exact position of the sign in the sheet. Using a simple black-and-white photograph, it was possible then to multiply the reproductions. Being cheap, quick and highly portable, the Dylux method was also praised for the high quality of

[20] Gravell T. L., "A New Method of Reproducing Watermarks for Study", *Restaurator*, No. 2, 1975 pp. 95-104

the images it produced, which have the advantage of being an actual size reproduction. Furthermore, the process might be performed under lighted conditions, since a short exposure of Dylux paper to visible light does not affect the final result. However, there are numerous drawbacks to this method: first of all, it captures both the ink and the watermark, meaning that the overlying written text creates a barrier for the passage of light, making the image less clear; second, the thickness of paper affects the final result, reducing the clarity of the image; third, even though some similar types of photosensitive methods are still in the trade, Dylux paper is no longer manufactured, and its shelf life of only three years in the best conditions.

The Ilkley Technique[21] was developed by Robin Alston in 1976, and requires two glass plates, a light source, Kodak Precision Line film and a dark room. The method consists of positioning a plate glass under the leaf that has to be examined, in turn covered by a second piece of glass. The assembled object is then exposed to light for 5 seconds, and the film is then removed and processed manually. After processing, the image of the watermark, together with the chain and laid lines and any other variation in paper surface will be visible on the film. However, the other details of paper, such as ink and writings overlying the watermarks will be recorded. Even being quick and cheap to realise, similar to the Dylux method, the Ilkley Technique can only be considered useful when analysing paper which has little to no surface obstruction.
Even though the methods just described have the quality of being fast and cheap, none of them seemed to be adequate for a precise watermark reproduction for bibliographical analysis, a problem which limited considerably their use.

2.1.4 - Radiographic techniques

The radiographic techniques for examining watermarks and leaf structure have been among the most popular approaches for bibliographical research on paper. Beta-radiography, slow X-

[21] Hiary H., *Paper-based Watermark Extraction with Image Processing*, cit., p. 21

radiography, and electron-radiography are the three primary radiography types utilised for this purpose[22].

One of the first methods advanced by the new wave of bibliographers was the use of beta-radiography. In the late 1950s, beta-radiography for paper studies was introduced by Dimitry P. Erastov from the Academy of Sciences of Leningrad[23]. Beta-radiographs are produced in a dark room environment by placing in close contact a paper leaf between a source of isotopes and a fine-grained X-ray film, sprinkled with radiographic emulsion. In particular, this technique makes use of a thin polymethyl methacrylate sheet labelled with radioactive carbon-14, an isotope which, while decaying, emits pure beta particles of low energy capable of penetrating the sheet of paper and recording its variations in thickness on the X-ray film. Carbon-14 is the perfect radioelement for this specific use because of its low emission energy of ß particles, which generates greater attenuation when passing through the examined material, leading to greater contrast in the final reproduction[24].

In order to guarantee the perfect contact between the three elements of the "sandwich", a glass plate or vacuum is applied to press the layers together and minimise air gaps, which would otherwise deteriorate the image quality. As explained by Vincent Daniels and Janet Lang in their article "X-rays and paper", 'this is necessary to ensure that the intensity of the radiation is reduced as little as possible by absorption in the air between the source, subject and film'[25]. After developing the film, the result is high quality and high contrast, one-to-one, black-and-white image of the watermark and other texture characteristics of the paper that is easily duplicable. The main advantage of this technique lies in the minimum interference of overlying writing and printing visible in the final reproduction: this is because layers of

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[22] For an introduction on the radiographic methods for paper analysis: Bridgman C. F., Radiography of Paper, *Studies in Conservation*, Vol. 10, No. 1, Feb. 1965, pp. 8-17; Daniels V., Lang J., "X-Rays and paper", in Lang J., Middelton A. (eds.), *Radiography of cultural material*, Second edition, Elsevier Butterworth-Heinemann, Oxford, 2005, p. 96-111; Tomimasu H. et al., "Comparison of four paper imaging techniques: B-radiography, electrography, light transmission, and soft X-radiography", *Tappi Journal*, Vol. 74, No. 7, July 1991, pp. 165-176

[23] Simmons J. S. G., "The Leningrad Method of Watermark Reproduction", *The Book Collector*, Vol. 10, 1961, pp. 329-332

[24] La Chapelle A. (de), "La bêtaradiographie et l'étude des papiers", *Gazette du livre médiéval*, Vol. 34, 1999, p. 14

[25] Daniels V., Lang J., op. cit., p. 97

organic ink or paint usually do not appear, as being composed of light elements like carbon, not capable of absorbing X-rays[26].

A major disadvantage of this acquisition method is its prohibitive cost: a plate layered with carbon-14 costs about $2,500. This makes it very difficult for a small institute or for individual scholars to have access to this type of technology. Furthermore, in order to buy and own one of these plates, a licence is required, and the operator has to be trained in the use and manipulation of radioactive materials, always handling it with thick rubber gloves. Numerous are also the healthy issues arose by scholars, both affecting the officer responsible for handling the radioactive plate and the source onto which the research is carried. The size of the final image is, moreover, limited to the size of the plate, meaning that if a bigger watermark has to be reproduced, some different and long procedures have to be executed to reach a satisfying result[27]. The longevity of the plate, which is not limited by the carbon-14 half-life, depends rather on the stability of the polymethyl methacrylate to the radioactive element within it, and to the physical and chemical environment in which it is stored. The average lifespan is now estimated to be around ten years.

Exposure time, which depends principally on the thickness of the paper source, was another con: the thicker a sheet of paper is, the longer the exposure time will have to be in order to reach a satisfying result[28]. A wrongly timed exposure would result in a blurred and unclear image of the watermark and paper structure. In the articles consulted for the writing of this thesis, the time of exposure suggested for beta-radiography varies considerably from source to source: Hiary speaks of two to twenty-four hours[29]; Schreiner et al. consider a time span of four to eight hours[30], Daniels and Lang refer to a range of five to twenty hours[31]. To speed up

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[26] Metal based inks or paint instead absorb the beta particles and may show on final radiographs.

[27] A description of a method for recording large watermarks with a beta-radiograph plate: Ash N., “Recording Watermarks by Beta-Radiography and Other Means”, *The Book and Paper Group Annual*, The American Institute for Conservation, Vol. 1, 1982

[28] Van Zweeden J., Beentjes L. B., *Exposure time determination in beta-radiography of watermarks*, “Quaerendo”, Vol. 12, No. 4, pp. 309-315

[29] Hiary H., *Paper-based Watermark Extraction with Image Processing*, cit., p. 25

[30] Schreiner M., Wallner-Holle H., op. cit., p. 144

[31] Daniels V., Lang J., op. cit., p. 97

the process, Carlo Federici suggested a way to use a single plate and a couple of sensitive films in order to collect two watermarks in one exposure time[32].

The study by Arianne de La Chapelle and André Le Prat dated 1996[33] contributed to the reduction of the lengthy exposure times required for beta-radiography by the use of fast Kodak DEF film: the exposure times were then reduced to under one hour. In the description of the protocol for beta-radiography at the paper lab of the Art Institute of Chicago, with the substitution of Kodak x-ray films with Regius FP-1S phosphor-coated imaging plates, it was possible to further reduce the time exposure for a high-quality watermark image to ten/forty minutes. These images are directly digitised and possible to manipulate via Image Plot Konica software[34]. However, this new type of setup, which is inserted in a scanner responsible for the automatic digitisation of images from the phosphor-coated plates, maintains its high costs of realisation. The scanning unit, in fact, costs around $50,000, which makes the system unaffordable for small institutes.

Soft or low-voltage X-radiography is another radiographic method used for the analysis of paper structure. Developed in the mid-1980s by Jan van Aken[35], it is based on the same principles of beta-radiography, however, solving the problem of the long exposure time needed for final reproduction. In a dark room condition, X-rays are radiated at low voltage energy (3keV-10keV: kilo electron volts) from a beryllium tube, the metal with the lowest absorption of X-radiation. The exposure time in which radiations pass through the sheet of paper and hit a radiographic film or phosphor plate lasts about 2 minutes. When low kilo-voltages are employed, the use of cassettes to protect the film from light can present a problem: in fact, conventional cassette materials may absorb a large proportion of the incident X-radiation. For this reason, much work on watermarks is done with the X-ray set in a darkened room, using a bare film in contact with the paper. As in beta-radiography, the advantages of using low voltage radiation show in the high quality of reproductions and sharpness of images. The technique was successfully adopted for the study of the paper used

32 Federici C., "Filigranes et bétagraphie", *Gazette du livre médiéval*, Vol. 4, 1984, p. 24

33 La Chapelle A. (de), Le Prat A., *Les releves de filigranes,* Musee du Louvre, Paris, 1996

34 Rivera Ramos M. C., Broadway M., *Beta Radiography Protocols: Watermark Wiki Submission*, The Art Institute of Chicago, 2019

35 Van Aken J., "An Improvement in Grenz Radiography of Paper to Record Watermarks, Chain and Laid Lines", *Studies in Conservation*, Vol. 48, No. 2, 2003, pp. 103-110

by Rembrandt[36]. A huge improvement was made in 1999, when the buffer of air which X-rays had to traverse from source to paper was substituted with a buffer of helium, reaching 99% of the radiations hitting the object. With the evolution of digital detector arrays, it was possible to substitute the X-ray films with imaging plates for computed radiography, less sensitive to visible light and thus possible to be exposed under subdued light conditions. Furthermore, a lower exposure dose and computer-aided interpretation and analysis of the resulting digital radiograms lead to an almost obvious preference for computed systems rather than classic film radiography. The modern radiographic images are either collected on reusable phosphor imaging plates that are then scanned (indirect capture or computed radiography, CR) or captured by a digital detector (direct capture or direct radiography, DR)[37].

The main advantage of this technique, as it is with beta-radiography, is the quality of the resulting reproductions of watermarks and paper structure, which are not covered by the overprinted or overwritten ink. The possibility to produce in a single, shorter exposure time the image of an entire sheet is the main distinction from the previous method, which makes soft X-radiography a more suitable and up-to-date technology for paper studies. High costs, however, have to be considered when approaching this reproduction technique, which are even more substantial than in beta-radiography. Another limit remains the capacity of metallic elements in paper to absorb X-ray energy which, similarly to beta-radiography, can affect the final resulting image.

The last radiographic method used for watermark reproduction and study, technically similar to beta-radiography, is electron-radiography[38]. Differently from soft X-radiography, the image is not produced directly by the impact of X-rays onto paper, but rather by electrons. These electrons are emitted when the X-rays at very high energy irradiate a foil of heavy metal material (usually lead) and, having sufficient energy to penetrate paper, reach a sensitive film or an imaging plate, recording any change in internal paper structure. The X-ray beam emitted is generated at high voltage, around 150-450kVp, and hits the lead foil. This undergoes an

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[36] Laurentius T. et al., "Het Amsterdamse Onderzoek naar Rembrandts Papier: Radiografie van de Watermerken in de Etsen van Rembrandt", *Bulletin van het Rijksmuseum*, Vol. 40, 1992, pp. 353-384

[37] https://mci.si.edu/digital-radiography, *Digital Radiography*, Smithsonian Museum Conservation Institute. Last visited 25/07/2023

[38] Schnitger D., Mundry E., "Elektronenradiographie, ein Hilfsmittel fur die Analyse von Wasserzeichen und Miniaturmalereien", *Restaurator*, Vol. 5, No. 1-2, 1983, pp. 156-164

internal photoelectric effect, in which an increased amount of surface electrons are able to escape the foil and reach the detector, irradiating it. Tight contact between foil, object of research and detector is essential, since electron emission released by the foil is diffused and becomes even more sparse when passing through the paper source. In order to avoid a final blurred image, the space between foil, specimen, and detector has to be minimal. The X-rays generated are too high an energy to expose the film, so they do not affect the final reproduction result. As in the other radiographic methods, the evolution of digital tools replaced the use of sensitive films (used under darkroom conditions) with imaging plates, which are reusable and directly scanned by systems of computed radiography. The exposure time needed for this type of technique is a matter of a few minutes, being the fastest radiographic method for watermark registration. Since electrons are not affected by the presence of any metallic material, this technique can be used also with sources covered by metallic-based ink writing and printing without any consequence on the final reproduction.

2.1.5 - Near-infrared technologies and thermography

Considering the electromagnetic spectrum section of longer wavelengths, infrared technologies are also used for research in watermark studies. These types of inspections analysed the way in which infrared waves pass through paper, enhancing watermarks and paper structures. This is because most of the different types of ink are invisible in the infrared wavelengths, which at the same time are scattered or absorbed differently by the paper and the watermark.

In the study by Peter Meinlschmidt and Volker Märgner[39], some experiments were made placing paper between a CCD camera, sensitive to visible and near-infrared light between 400 and 900nm (extension of the visible spectrum), and a source of homogeneous white light. In order to reduce the interference of handwriting in iron-gall ink, a narrow bandpass filter centred at 780 or 830nm of wavelength was placed in front of the camera. It was observed

[39] Meinlschmidt P., Märgner V., “Multispectral Image Archiving of Watermarks in Historical Papers”, *Proc. IS&T Archiving Conference 2011*, 2011, pp. 92-96; Meinlschmidt P., Kämmerer C., Märgner V., “Thermographie – ein neuartiges Verfahren zur exakten Abnahme, Identizierung und digitalen Archivierung von Wasserzeichen in mittelalterlichen und frühneuzeitlichen Papierhandschriften, -zeichnungen und -drucken”, in Fischer F., Fritze C., Vogeler G. (hrsg.), *Codicology and Palaeography in the Digital Age 2*, Books on Demand GmbH, Norderstedt, 2010, pp. 209-226

that images taken at 830nm appear less affected by the presence of writing. However, a kind of ghost image of writing which could not be suppressed in the near-infrared remained visible anyway.

This prompted scholars to further investigate the application of infrared waves, moving from near-infrared (0.7μm to 3μm) to thermal mid-infrared spectrum ranges from 3μm to 7μm (MWIR). Writing ink on paper does not absorb thermal radiation, which means that printing is not overwritten in the final images. This technique makes use of thermographic systems detecting mid- or long infrared wavelengths, which means they are highly sensitive to temperature differences, in front of a thermal source (warm copper plate) at a temperature of 35 to 40°C. The paper sheet is placed upon a frame called "passepartout", which ensures the correct distance from the heated plate. The infrared radiation emitted by the plate is transmitted through the paper, which absorbs it differently depending on the thickness and density of the sheet. The variations are recorded by the camera and saved to connected computer. The result is a thermographic image in which thinner areas of the sheet of paper, including the watermark and the other structural characteristics of the leaf, are represented as white lines on a darker background. The exposure time is of few seconds, in which the camera captures a series of images and transmits them to the connected PC. The final images are clear and sharp, not showing any interference from overlying ink. The major limitation is concerned with the safety of the watermarked paper, which has to stay at a certain distance from the warm copper plate and be exposed for the shortest time possible. Further explanation of this technique will be deepened in Chapter 3.2, dedicated to the DRACMarkS project.

2.1.6 - Multispectral imaging

Among the most recent technologies being developed for the reproduction of watermarks and the study of paper artefacts in general, Multispectral Imaging Systems (MSI), relying both on hardware and software, is one of the most acclaimed. These systems are used to produce numerous exposure sets in a wide variety of wavelength ranges, including those outside the visible colour spectrum, which are generated and integrated using completely automated procedures in a matter of seconds. In addition to the instant creation of multiple images in a single exposure, these systems are capable of automatically calculating and returning the reproduction of the paper structure and watermarks, as described in Chapter 2.1.2, owing to the processing of reflected and transmitted light images. In particular, the software performs a process of "phase-shift": via an equalisation operation, matrix division and optimising ratio between the images, it is possible to enhance the visibility of the watermark and to reduce the interference of the ink in the paper. In general, the possibility to create simultaneously an image of the visible page with the writing or drawing together with an image of the paper structure and the watermark makes the archiving process simpler. Furthermore, this also permits a more detailed analysis of the paper characteristics without the need to examine the original. When having access to powerful hardware and software systems, this method proved to be easy, safe and quick to perform. Some pictures created with an MSI may be found on the website of The National Archives Collection Care department[40], in which various analyses on paper sources were performed in single-shot images.

Multispectral Imaging Systems remain elite instruments, expensive and difficult to transport, affordable only for a close number of institutions. The standardisation of the images produced, however, will certainly help in the future of watermark reproduction development.

2.2 - Watermarks repositories and databases

Repositories of watermark reproductions are a crucial tool for bibliographical research on paper. These collections give the possibility to compare and look for matching watermarks among a vast selection, in terms of similar or identical design. The first watermark collections appeared in the 19th century and most often were taken from a single source repository. Nowadays these catalogues are published as online databases, becoming more and more furnished with updated images and information, including watermarks from numerous different European collections. These digital libraries make watermark data more accessible, facilitating their analysis and study. However, the building of online repositories for filigranological studies has proved to be challenging, considering the vast variety of reproduction techniques and description procedures. In the next chapter, a general overview of

[40] https://blog.nationalarchives.gov.uk/watermarks-new-ways-to-see-and-search-them/, Pereira Pardo L., Bergel G., *Watermarks: New ways to see and search them*, Archives and archivists, Technology and innovation, 30 July 2020. Last visited 26/07/2023

the evolution and current situation of digital databases will be described, focussing on the case of the Bernstein Portal and the Wasserzeichen-Informationssystem (WZIS).

2.2.1 - The printed watermark repositories

The first watermark repositories date back to the first half of the 19th century with the consciousness of the usefulness of these paper signs as instruments for historical research. In the second half of the same century, vast and important collections of reproductions were created, among them those curated by Aurelio Zonghi and Friedrich Keinz, great pioneers of filigranology, established a foundation for further research. Zonghi dedicated himself to the research of the medieval watermarks of Fabriano and the surrounding regions, publishing two collections containing a total of 1,887 watermarks. The categorisation followed is based on watermark motifs, and within each category, they are distinguished on the base of their dating. Friedrich Keinz used instead a classification based on four main groups of objects (line tracings, humans, animals and plants), including references to identical or similar watermarks contained in other published collections[41].

At the beginning of the 20th century, an important repository created by the celebrated paper dealer Charles-Moïse Briquet set a decisive turning point in the history of watermark collections. In 1908, he published his magnum opus, *Les Filigranes*, containing around 16,100 reproductions of the 44,000 collected by the Swiss scholar. The true objective of Briquet, rather than simply creating a repository of watermarks, was to pinpoint the first appearance of a certain design and of its variants. In the introduction to his work, he discussed the way in which he decided to order and categorise the collection and how other authors opted for general categories, e.g. the ones used by Keinz. However, from his point of view, this method did not attain the goal of a simple and rational classification which would permit a fast and easy way to retrieve the watermark of interest. Zonghi supported the idea of chronological order, having the flaw of being difficult to modify whenever a new watermark was found and had to be inserted in the list. Another idea was to classify via nationality, which Briquet describes as impossible to achieve. The only method that seemed to answer all the necessities was an alphabetical order, especially considering the non-expert readers that

[41] Rückert P., Hodecˇek S., Wenger E. (eds.), *Bull's Head and Mermaid*…, cit., p. 79

approached these kinds of collections[42]. For each category of watermarks, Briquet first gave a general introduction about the sign design, where it was normally used and in which period. A final category, named “Uncertain”, collects all the watermark designs of doubtful meaning. He also pointed out the earliest example found for every watermark, dividing the single categories (e.g. “Agneau pascal”, Easter lamb) into enumerated smaller groups on the basis of their tiniest differences. Then, a list of watermarks is presented, in which the dimensions of paper sheet, the place of use, date of use, repository and title of the work or document in which the sign was found are recorded. For each smaller group, one or more examples of the same design may be noted, but only one tracing for each will be shown. For a small number of tracings, Briquet recorded also the presence of twin watermarks, differentiating between *filigranes identique*, *filigranes similaires*, and *filigranes divergente*. These definitions are quite misleading and not consistent throughout the catalogue, reducing the usefulness and usability of his research, as outlined in the *Addenda* of the later version of *Les Filigranes* curated by Allan Stevenson[43]. Still missing is the information about the side chosen to look at paper, that is the felt or mould side.

Numerous print collections have been published since *Les Filigranes*, trying to follow and enlarge the example given by Briquet. The *Findbücher*[44] by Gerhard Piccard created the largest printed repositories of watermarks, containing approximately 44,500 individual sign tracings, divided into 4,540 different types. Published between 1961 and 1997 in seventeen parts and composed of twenty-five tomes, the work is organised thematically, each supplied with an introduction and description of each watermark design, their historical context and place of retrieval. Furthermore, the description of each single design includes the placing of the watermark on the chain lines, and the number of wirelines covered by the watermark, not reporting instead the measurement of the sheet and the place in which the document is currently held. The information about the side from which the tracings were made is also missing, as is the original position of the watermark inside the mould. However, some of the

[42] Briquet C. M., *Les Filigranes…*, cit., p. 16

[43] Briquet C. M., *Les Filigranes ... a Facsimile of the 1907 Edition with Supplementary Material contributed by a Number of Scholars*, Stevenson A. (ed. by), Amsterdam, The Paper Publications Society, 1968, p. 18

[44] Piccard G., *Findbücher der Wasserzeichenkartei Piccard im Hauptstaatsarchiv Stuttgart*, 17 Bde., Veröffentlichungen der Staatlichen Archivverwaltung Baden-Württemberg, Stuttgart, 1961-1997

marks contained in the collection are described as being twins, though he didn't reference a sufficient number of sources to make that information reliable.

Two other major printed watermark repositories, closely connected to each other, have to be mentioned: the works of William A. Churchill and Edward Heawood, both of them following the method used by Briquet. The earliest is *Watermarks in Paper in Holland, England, France* by Churchill[45], published in 1935 and surveying watermarks of North-Western Europe and giving a general overview of paper production in that area, especially in Holland. They are 578 tracings that are not perfectly executed and do not reference the wire and chain lines. The second repository, *Watermarks mainly of the 17th and 18th centuries*[46], was published by Heawood in 1950 and comprises a total of around 4,000 tracings. The focus of this study is mainly on watermarks contained in maps and printed books from the library of the Royal Geographical Society, the Victoria and Albert Museum and the British Museum. Heawood, mainly tracing watermarks from Northern Europe, frequently consulted the work of his friend Churchill, using many of his reproductions but never directly publishing them in his work.

2.2.2 - The passage to digital: online databases of originally printed repositories

The two most important printed repositories, *Les filigranes* by Briquet and the *Findbücher* by Piccard, have been digitised and catalogued in dedicated online databases. The necessity for the creation of these digitised collections was because of the crucial role of these fundamental pieces of filigranology, which should be accessible by everyone, everywhere, to be able to retrieve information easily. As stated before, these kinds of repositories are not that useful for recognising the twin or mould-mate watermarks but are instead functional for a first identification and general collocation in time and space of these signs.

The necessity of publishing and organising a vast portion of Piccard's collection which remained undiscovered to the public, beyond the ones that were already included in the

[45] Churchill W. A., *Watermarks in paper in Holland, England, France, etc. in the XVII and XVIII centuries and their interconnection*, M. Hertzberger, Amsterdam, 1935

[46] Heawood E., *Watermarks, Mainly of the 17th and 18th Centuries, The Paper Publications Society*, Hilversum, Holland, 1950

seventeen tomes of the *Findbücher*, led to the idea of creating Piccard-Online[47]. The project would contain the entire Piccard Index of the Hauptstaatsarchiv Stuttgart. The first part of the work consisted of ordering, classifying and digitising the unpublished tracings, added eighteen new groups to the originals created by Piccard. The second part of the project dealt with the indexing and integration of the other watermark reproductions into a new structure. Together with the images information that Piccard noted about each watermark, is transcribed into the online database, including the position with respect to the laid lines, date and location of the manuscript, etc. The introductions to each category and general information about the research method contained in the original version of the *Findbücher* are also reported in the online database. Watermark research in Piccard-Online follows the example of the printed repository, basing itself on visual representations and helping the less experts approach the browsing of watermark images. The classification of watermarks is organised via a hierarchical tree structure, in which general categories like "lily" or "fabulous creature" are divided into smaller subgroups on the basis of their specific characteristics. This is divided into subsequent smaller groups, each containing even more detailed information about the particular attributes of the watermark. When approaching the "Structured view"[48], in fact, a page divided into two sections opens up: on the right, the visual navigation is shown, in which prototypes of the different motives are found, making it possible to browse the repository via images; on the left, instead, the hierarchical structure of the various categories is shown as a cascading menu, so that the user can search and browse also using simple and non-technical descriptions. At the end of each branch in the hierarchical structure of the database, a list of the watermarks available for that specific design in Piccard Index is displayed. When clicking on the specific item, a separate card opens up revealing an enlarged image of the watermark, combined with a ruler for measurement. Other two bottoms give the possibility to mirror the image if necessary and download the PDF version for printing. This last feature is useful for those willing to compare directly a watermark design with another supposedly similar or identical one. In order to enable clear and permanent referencing and citation, a permalink is

[47] Rückert P., "Piccard online. Die digitale Präsentation von Wasserzeichen als neue Forschungsperspektive", *Gazette du livre medieval*, No. 50, 2007, pp. 40-50

[48] www.piccard-online.de/struktur, Piccard-Online, *Piccard Watermark Collection, Structured view*. Last visited 07/08/2023

appointed to each watermark as a persistent identifier[49]. The description of watermarks is, however, not entirely normalised, with book numbers, descriptions and dates showing a considerable degree of variance.

Additionally to the option of exploring Piccard repository via browsing, it is possible to search watermark designs via full-text search, which might be useful for those scholars already aware of specific descriptive terminology for watermarks, or willing to look for designs originated in some specific geographical areas or manuscripts preserved in determined repositories, dated in a specific timeframe. All these parameters can be managed and changed using the "Full-text search" tool, which is available in three different languages, English, German and French[50]. In 2016 Piccard Online was included in the WZIS database, described in Subchapter 2.3.3.

A second project aiming to transfer an originally physical repository into an online database is the "BO - Briquet Online" project[51], promoted by the Laboratoire de Médiévistique occidentale de Paris (LAMOP) in the 1990s and now passed to the Austrian Academy of Sciences (ÖAW)[52]. Much simpler in its structure compared to the previously described Piccard-Online, the homepage of BO appears as a list of terms in German and French ordered alphabetically and thus following the original classification of Briquet's printed catalogue. Each term is selectable, opening up a new page in which a further division based on specific characteristics of each design is outlined. When clicking on one of these subcategories, a list of single watermarks appears, identified by Briquet's code number and recalling the original repository positioning. When further clicking on this code, a new page opens revealing the watermark appearance and the other specific related information noted by Briquet, like measurements of watermark size and position compared to laid and chain lines, the repository of the manuscript and its dating. The other two links give respectively the possibility to download a PDF format of the single card and to view the specific page of the original printed repository in which the watermark is mentioned. The possibility for a simple search via

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49 Maier G., Wolf C., "Piccard-Online und der Aufbau eines 'Wasserzeichen-Informationssystem Deutschland'", in Rückert P., Frauenknecht E. (hrsg.), *Wasserzeichen und Filigranologie. Beiträge einer Tagung zum 100. Geburstag con Gerhard Piccard (1909-1989)*, W. Kohlhammer, Stuttgart, 2011, p. 68

50 Rückert P., Hodeč̌ek S., Wenger E. (eds.), *Bull's Head and Mermaid…*, cit., pp. 87-89

51 briquet-online.at, BO - Briquet Online, *Hompage*. Last visited 08/08/2023

52 Harris N., Pastrolin I., *Briquet Reloaded*, Institut d'Histoire du Livre, Lyon, 2018, p. 160

Briquet-Nummer is also given, which however is fruitless if the user does not know the original coding of the specific watermark in Briquet's repository. Further development would be to improve the search tool via a simple description of the watermark design, the place of origin of the manuscript or its dating. The database is intended to be upgraded by including watermarks cited by Briquet but reproduced in other repositories, and the other watermarks gathered by Briquet but not published on his *Les Filigranes*[53].

The usefulness of having such eminent repositories in a digitised form, designed for both scholars and non-experts, certainly transforms the already precious printed catalogues into a new tool for filigranological research. The main characteristic of these online databases of former physical collections is the maintenance of the original classification of watermarks, not being modified in the digitised version and following the decisions respectively taken by Briquet and Piccard. This follows the idea of a concrete online transposition of the printed works, without any intervention to modify or critically edit any of the original categories. In this way, a first glimpse into watermark classification and identification previously performed using printed repositories is now quicker via browsing images or short and clear descriptions.

2.2.3 - Online native watermark repositories

Differently from the just described online databases, numerous collections of watermarks did not originate as a pre-existing printed catalogue but were designed in their digital form. Starting from scratch, the majority of these database projects began with the identification of a location or time frame of interest then moved to the reproduction of single watermarks from original sources if not already available.

The first example of this database type is the project developed by Gerdard van Thienen and his successor, Marieke van Delft, called Watermarks in Incunabula printed in the Low Countries (WILC)[54]. This online database contains the reproduction of 16,000 watermarks found in approximately 1,800 incunabula printed in the Netherlands in the 15th century, of which only 800 were dated. The WILC project aimed to retrieve, reproduce and publish these

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[53] Haidinger A., "Gedruckte Wasserzeichenrepertorien und as World Wide Web", in Rückert P., Frauenknecht E. (hrsg.), *Wasserzeichen und Filigranologie…*, cit., p. 21

[54] watermark.kb.nl, Watermarks in Incunabula printed in the Low Countries (WILC), *Introduction*. Last visited 08/08/2023

watermarks in order to determine a final dating of the sources or at least to restrict the possible date to a number of years[55]. One of the most important aspects of this research was the use of rubbing (for 2/3 of the watermark reproductions) and electron radiography (1/3 of the images) for watermark reproduction rather than tracing, a method considered to be too imprecise, as explained in Chapter 2.1.1. Praised also by Neil Harris, the work has been called 'the biggest single step forward since Briquet'[56], because of the quality of watermark images and for the extensive bibliographic analysis and information along with the reproductions available on the website. All the images were described and uploaded into an MS Access Database, employing the "English Typological Index" added by Stevenson to the 1968 edition of Briquet[57]. Using an advanced search query, it is possible to retrieve results by a general description of the watermark design and meaning, place or date of printing, name of the printer, etc. These parameters can be used alone or combined using boolean operations. Once the search is completed, a list of marks appears, viewable also in gallery mode. When clicking one of these single designs, further characteristics and information are shown: a standardised description followed by the IPH classification of the watermark (only the main class), its position inside the sheet (left or right side), an indication of the chain line number between which the mark is found, together with the distance between the lines. Furthermore, a detailed description of the watermark location inside the source incunabula is given and, when possible, a reference to probable twin marks[58]. Images of the same watermark in different editions are also noted, indicated as equivalent and listed in equivalent groups. The information about the source is limited to details relevant to paper historical research: a reference to the institution where the source is preserved, the number of leaves of the copy, and other production details, like printer, city and date. Each item in WILC is linked to the Incunabula Short Title Catalogue (ISTC), which is an international database of 15th century printing recording nearly every item printed from movable type before 1500. Thanks to the link established with this important database, a complete description of the source of each

55 Needham P., "IDL, ILC, WILC: Gerard van Thienen's contributions to the study of incunabula", *Quaerendo*, Vol. 36, 2006, pp. 3-24

56 Harris N., *Paper and Watermarks as Bibliographical Evidence*, cit., p. 150

57 Briquet C. M., *Les Filigranes ... a Facsimile of the 1907 Edition with Supplementary Material contributed by a Number of Scholars*, cit.;

58 Rückert P., Hodecˇek S., Wenger E. (eds.), *Bull's Head and Mermaid*..., cit., pp. 92-94

watermark can be retrieved easily[59]. Some of the watermarks stored in the WILC collection are also present in Piccard's *Findbücher*. For this reason, nearly 1000 watermarks in WILC reference the *Findbücher*, exploring also the possibility of creating a connection between WILC and Piccard-Online directly.

Another example of a digital-native database of watermarks is the Database of Watermarks and Paper Used for Prints and Drawings Developed by the Dutch University Institute for Art History in Florence, also called NIKI[60]. This project, which began in 2001, focuses on the digitisation and collection of watermarks contained in paper used by artists for prints and drawings in the period between 1450 and 1800[61]. It is also possible to create a personal account as an "author-curator", granting the ability to modify already existing cards or create new ones via simple uploading of watermark images and information. The idea is to create a participatory collection of watermarks, open to new uploads by every scholar interested and in possession of any relevant source. The NIKI project itself has collected images and data from paper used by different artists, including Fra Bartolomeo, Michelangelo, Rembrandt and Ludovico Cigoli[62]. Furthermore, it is possible to navigate this database via a simple or advanced search of watermarks, showing the results in a listed form. When clicking on the single watermark, a new page opens up showing various information about the watermark, explorable via the menu on the left or using the arrows "back"-"next". These include four general categories: source, paper, watermark and image. Each of these has its own subcategories, deepening information about the artist and the title of the work, and further data on format, provenience and manufacture of paper. The classification of the watermark is done following the IPH standards and via comparison with other systems like Briquet and Piccard. It is also possible to find the dimensions of the watermark and the presence of potential equivalents inside the database. Finally, a section is dedicated to the images and

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59 van Delft M., "Watermarks in Incunabula printed in the Low Countries (WILC) and Piccard-Online. A Comparison of two important Watermark Databases and Research Prospects for Combining their Data", in Rückert P., Frauenknecht E. (hrsg.), *Wasserzeichen und Filigranologie…*, cit., p. 91

60 www.wm-portal.net/niki, NIKI, *Homepage*. Last visited 09/08/2023

61 Rückert P., Hodecˇek S., Wenger E. (eds.), *Bull's Head and Mermaid…*, cit., p. 97

62 Meucci A., "Database internazionale di filigrane e carta usata in disegni e stampe (C. 1450-1800)", Mitteilungen des Kunsthistorischen Institutes in Florenz, 2008, 52. Bd., H. 2/3, *La tecniche del disegno rinascimentale: dai materiali allo stile. Atti del convegno internazionale Firenze*, 22-23 settembre 2008, p. 275

closeups of the watermark in question. These were mainly created using soft X-ray and image subtraction technologies.

The last project presented in the category of digitally native watermark databases is the Watermarks of the Middles Ages or "Wasserzeichen des Mittelalters" (WZMA)[63], supported by the Kommission für Schrift- und Buchwesen des Mittelalters of the Austrian Academy of Sciences, began in 1999. During the cataloguing of the manuscript holdings at the Klosterneuburg Stieftsbibliothek, questions about the numerous undated sources arose[64]. The idea was to create a database of the Klosterneuburg manuscripts and their watermarks, then clustered into WZMA together with other watermarks coming from different repositories. By using beta-radiography for watermark imaging, WZMA principal aims were to create a concrete watermark repository and to chronologically sort undated Austrian manuscripts from the Middle Ages[65]. By now the database contains around 21,000 watermarks from 36 different repositories located all around Austria, dating from 15th to 17th century.

The system used for searching watermarks works similarly to the one described for Piccard-Online, with a gallery of icons or a list of watermark motifs from which a cascading and hierarchical structure opens up. This strategy helps to bypass the problem of recognition and terminology in watermark analysis, which might result in ambiguity. Each main group contains other subcategories, with most specific characteristic of each watermark design in order to reach a final restricted list of motifs. By clicking on one of the resulting watermarks, a new card pops up coming with all the major information useful for bibliographical research. Apart from general measurements of the watermarks and distance between chain and laid lines and provenience, the presence of twin marks is reported, together with other correlated signs present in the collection. Other useful tools available are the possibility to mirror the image of the watermark, to invert colours of the reproduction, and to intensify or decrease brightness. Among this data, a complete list of the other watermarks present in the same manuscript is also linked. The search tool and website are available in eight languages and

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63 www.wzma.at, WZMA, *Homepage*. Last visited 09/08/2023

64 Stieglecker M., "Wasserzeichen in des Mittelalters (WZMA) und Piccard-Online. Vom gegenseitigen nutzen", in Rückert P., Frauenknecht E. (hrsg.), *Wasserzeichen und Filigranologie…*, cit., p. 79

65 Haidinger A., "Die Sammlung *WZMA – Wasserzeichen des Mittelalters* der Kommission für Schrift- und Buchwesen des Mittelalters", in Rückert P., Godau J., Maier G. (hrsg.), *Piccard-Online Digitale Präsentationen von Wasserzeichen und ihre Nutzung*, Verlag W. Kohlhammer, Stuttgart, 2007, p. 47

connected also to manuscripts.at[66], a web portal for medieval manuscripts in Austria, to ensure the results presented in WZMA. The uniqueness of this project compared to other watermark databases is the registration of all watermarks from each historical manuscript, entering in the final format only a single record from each source.

The development of these databases has set a methodological basis for the development of further online collections of watermarks, limited to single geographical areas and repositories. The need for an aggregating system for the comparison of watermarks, however, was growing and consistent. That is why the content of WILC, NIKI and WZMA, together with Piccard-Online, gave the basis for the creation of the Bernstein Portal, The Memory of Paper, which will be described in the following chapter.

2.2.4 - Aggregator watermark databases: the Bernstein Portal and the WZIS database

In order to develop a strong bibliographical reference and dating using watermarks, a large amount of records and data is necessary. Single databases described in the previous chapters represent a first step towards more complete and consistent repositories of watermarks, even though still not sufficient. In fact, as the number of single watermark databases grew, the necessity of creating a system capable of connecting all these collections became increasingly evident. The more data a database contains, the stronger and more helpful it becomes. An interconnected network may be used to create a centrally controlled and accessible data pool that stores all the information from the different databases.

The construction of such a gateway, which first connected the four largest watermark databases Piccard-Online, WILC, NIKI, and WZMA, is the goal of the Bernstein Portal[67]. Supported by the European Union via the eContentplus program, the Bernstein "Memory of Paper" Consortium was launched in September 2006 and it is still ongoing[68]. Nine partners

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[66] manuscripta.at, Manuscripta, *Homepage*. Last visited 09/08/2023

[67] www.memoryofpaper.eu/BernsteinPortal, Bernstein - The Memory of Paper, *Hompage*, Last visited 10/08/2023

[68] The activity of the project seems, however, to have slowed down with the official end of the financing program in 2009

were involved in the creation of the portal[69] which aims to create an international network of watermark databases, equipped with a search engine to retrieve data from the single repositories. As of April 2023, the portal supports 53 watermark collections and more than 320,000 watermarks from 22 countries. Many of these databases have their own server and different structures independent from the platform, even though they are well-integrated into the Bernstein system. This allows single institutions in charge of the various databases to manage and upload new data freely. The already existing watermarks digital repositories (Piccard-Online, WILC, NIKI, and WZMA) have been linked together to establish an integrated system by means of a common and uniform workspace, enabling simultaneous searches across all four databases. It was decided not to create a copy of the existing collections, but to implement searches via the Bernstein portal directly on the original databases. The installation of an SRU gateway (Search/Retrieval via URL), a common protocol for Internet search requests, was used to accomplish this goal[70]. All the new online repositories created after the opening of the Bernstein Project have the ability to use specific software specially designed for the implementation of local watermark databases, the Paper Studies Kit, also called the Dissemination Kit. The resulting database respects and follows the standard of the Project and might thus be integrated easily into the portal.

It was fundamental for the correct incorporation of the diverse databases involved in the project to set a textual watermark description standard, in order to achieve two main goals: a common multilingual nomenclature and a standard description and hierarchical classification of watermarks. This work proved to be difficult and time-consuming, requiring huge interventions and changes to the individual databases. Just consider that the terminology in the two largest databases, WILC and Piccard-Online, coincided only for 68.5%[71]. The results of this standardisation are the Bernstein Systematics (available in six languages)[72] and

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[69] These include: the Austrian Academy of Sciences as lead partner, together with the Archives of the State of Baden-Württemberg in Stuttgart; the Graz University of Technology; the Centre National de Recherche Scientifique, University of Paris I; the Deutsche Bucherei in Leipzig; the Dutch University Institute for Art History in Florence; the Delft University of Technology; the Koninklijke Bibliotheek in The Hague; and the University of Liverpool

[70] Rückert P., Hodecˇek S., Wenger E. (eds.), *Bull's Head and Mermaid…*, cit., p. 103

[71] Wenger E., "Bernstein. Ein EU-Projekt zur Papier- und Wasserzeichenforschung", in Rückert P., Frauenknecht E. (hrsg.), *Wasserzeichen und Filigranologie…*, p. 56

[72] Frauenknecht E., Rückert P., Stieglecker M., *Bernstein Systematics*, Version 1.6.1a, 2012

Watermark-Terms (translated into nine languages)[73], two lists of terminologies and classification structures for watermarks which are constantly updated. The classification and terminology differentiate from the already described IPH standard since the Bernstein classification directly originated from the one developed previously by Piccard and transposed into Piccard-Online. However, similarly to IPH, Bernstein Systematic maintains a tree structure based on three levels: class, subclass, and subgroup[74], which contain numerous different types of the same watermark motif.

When looking for a watermark inside Bernstein Portal search tool, three options to obtain the desired results are available: simple search, advanced search, or browsing motifs. The multilingualism of the platform allows the user to formulate their motif search in their own language: in fact, the user's language, if included among the ones supported by the portal, does not affect the results, since the engine automatically translates the input and returns the same outcome indifferently from the language used. The simple search consists of entering a term inside the searching field, and the inspection is carried out on the entire collection of fields of the database. When using advanced search, the user can combine several search fields, define single dates or intervals, and utilise specific search items that are not present in all databases. Browse motif search is identical to the one seen in Piccard-Online, in which it is possible to use names or icons to move about the tree structure. Before running the search, there are three options that may be used to set some parameters on the final results. Specifically, the users can freely select the specific databases (all selected by default) in which they would like to implement the search, the time frame of interest and the final visualisation mode. In fact, any subset of watermarks resulting from a search can be displayed in three ways: a list of the found items (visible also in grid mode), statistical characteristics of the returned subset, and geographical distribution using cartographic mapping. The primary metadata and a replica of the watermarks are displayed when the list visualisation mode is selected. By clicking on the single image, a card containing the information about that specific watermark pops up. This includes all the watermark's dimensions, place and date of use, depository, Briquet Number and IPH Mainclass, and the database from which the watermark is extracted. Furthermore, the code of the twin mark, and the names of the paper

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[73] Frauenknecht E. et alia, *Watermark terms*, Version 1.6.1a, 2012

[74] Müller E., "Describing and Representing Watermarks. From Paper Catalogues to Online Databases", cit., p. 126

mill and the papermaker responsible for producing the sheet of paper in question are included if known. If complete, this list of data creates a complex and detailed description of the watermark and its characteristics.

The ability to visualise the results in the form of a series of statistical graphs is one of the most acclaimed features of the Bernstein project: as shown in Fig. 3, by inserting a keyword (in this example, “Lily”, a type of watermark design belonging to the class “Flora”) in the search bar and selecting the statistics visualisation, the results are plotted in six graphs.

Fig. 3 - Results of a “Statistics search” on the Bernstein Portal by inserting the key-word “Lily” in the search bar

The first graph on the top left shows the results regarding the percentage of types related to the keyword “Lily” (2.03%) compared to the total number of types in the database, plotted as a pie chart in which the number of types in the selection is shown in red. The other two pie charts in the row illustrate the relationship between the number of watermarks place of use in selection and the total, and the number of repositories preserving a document containing a watermark representing a “Lily” compared to the total number of depositories. The second row of plots explores a series of quantitative values, like the average date of the motif’s use, its height and the distance between chain lines. These three charts take into consideration different values, including the maximum and minimum, the arithmetic mean and the standard deviation.

Apart from these six plots, created automatically whenever the statistics research is selected, the portal offers the chance to change the values of analysis using a matrix and create new plots. An example is shown in Fig. 4, in which it was possible to explore the relationship between a qualitative value (Place of use) and a quantitative value (Date) of the use of Lily as a motif in watermarks, resulting in a dot plot.

This type of analysis is extremely useful to whoever is exploring a specific type of watermark and needs a comparison using statistics values.

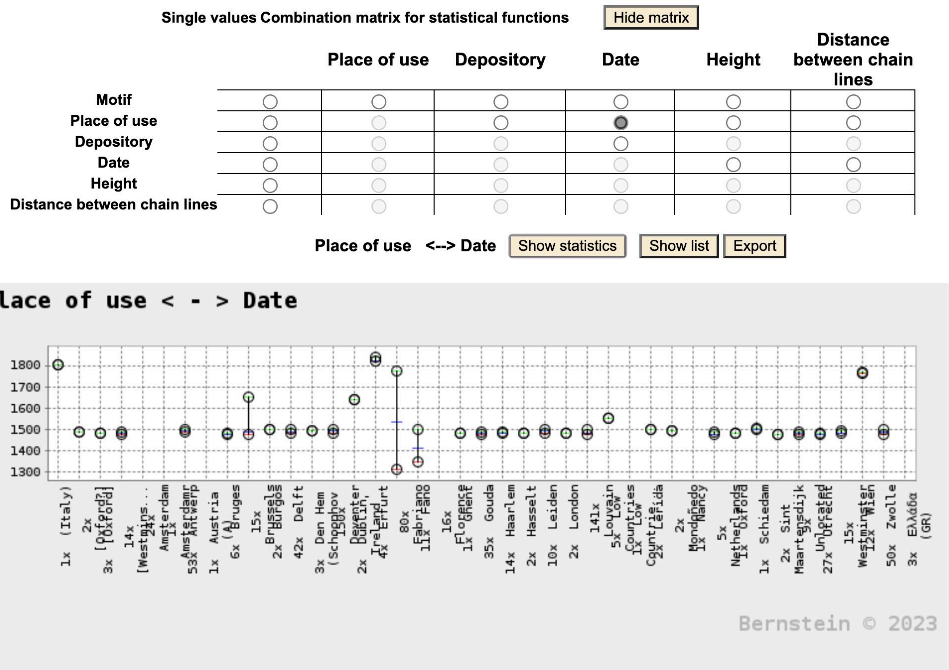

Fig. 4 - Dot plot showing the relationship between the date and place of use of the "Lily" motif

Another interesting feature of the search tool in the Bernstein portal is the cartographic distribution of the selected motif, in which a geographical map shows the results of the research as distribution in terms of place of use and frequency. In order to make this tool available, geographical indications in the databases have been standardised and geo-referenced. The possibility to export data is another useful extension for further research on the resulting watermarks.

In addition to the section on watermarks, Bernstein provides a research tool for the vast bibliographical list available on the website, following the original idea of offering a portal for the study of paper in the most complete way. This contains more than 31,000 bibliographical records of publications in various languages on historical, technological, commercial and social aspects of paper that have been published to date[75].

The portal was also responsible for the development of different software to enrich and help experts in the research on watermarks. Three are the main downloadable programs: PAT, which is the Paper Analysis Tool, determines the number of wire and laid lines and the average distance between them; the AWDT, the Automatic Watermark Detection Tool, capable of detecting watermarks in X-Ray and back-lit images; QET, Quality Enhancement Tool, able to remove noise from watermark images so that the design and paper structure become more visible.

During the years after its creation, the Bernstein portal has increased its collection, including more and more databases and amplifying the network. Among these databases, a special mention should be given to the WZIS project. The Wasserzeichen-Informationssystem (WZIS)[76] is a watermark information system created in 2012 and funded by the Deutsche Forschungsgemeinschaft (DFG – German Research Foundation), aiming to build a tool for watermark research which would allow cross-disciplinary and -institutional communication. With the help of numerous different partners[77] of the DFG, the idea was to create a common watermark information system for all of these German manuscript centres, setting a common standard for the upload of information. In fact, each of these libraries and centres has catalogued extensive collections of watermarks using various different reproduction methods. These constantly growing repositories were, however, limited to local use, and the necessity for a wider and more structured showcase arose. The WZIS system was designed to enable the decentralised entry of data, both images and metadata about each specific watermark, like the motif, place of description, manuscript containing them, etc. The decentralisation of data entering was achieved using an *Erfassungsmodul*, a recording module specially created for data entering and management. Watermarks are then coordinated and stored under a single interface in a uniform data structure using the "Watermark Toolkit", developed by Victor

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[75] Wenger E., "Bernstein. Ein EU-Projekt zur Papier- und Wasserzeichenforschung", in Rückert P., Frauenknecht E. (hrsg.), *Wasserzeichen und Filigranologie…*, p. 61

[76] https://www.wasserzeichen-online.de//wzis/index.php, Wasserzeichen-Informationssystem, *Hompage*. Last visited 11/08/2023

[77] These include: Württemberg State Library in Stuttgart (WLB), the State Archive of Baden-Württemberg (LABW), the Bavarian State Library in Munich (BSB), the University Library in Leipzig (UBL), the Austrian Academy of Sciences (ÖAW), the Berlin State Library (SBB), and the German National Library in Leipzig (DNB)

Karnaukhov for the Austrian Academy of Sciences, applied to the Bernstein project and adapted to the requirements of the DFG[78]. This software was developed in C++ programming language and allows the entering of watermark metadata via a user interface which is easily manageable and practical for the upload of information[79]. The system, however, remains based on centralised data management in a MySQL database located at the Baden-Württemberg State Archives in Stuttgart. The idea is to give a common access and standard to heterogeneous collections. For the digitisation of the single watermark reproductions, specific standards were set for image quality through the database: the picture resolution needs to be between 200 and 300 dpi, saved either in TIF or PNG format with a defined file naming scheme.

The project outline was based on the already existing database Piccard-Online then substantially revised. This revision consisted of an adaptation of the classification system and the addition of other watermarks images which were not included in the previous Online version but were part of the original printed repository. The insertion of the watermark image into the database follows specific steps for the evaluation of the watermark motif using a tree menu developed as part of the Bernstein project and its measurement via a semi-automatic tool to determine the height and the distance between chain lines (the PAT - Paper Analysis Tool, downloadable program offered on the Bernstein website). The classification model was designed to be dynamic, allowing for new categories as discoveries are made. Additionally, the database input allows the linking of multiple images to a single watermark card, including the main reproduction of the watermark, the countermark and the possible twin marks. These images are managed using single system-internal IDs and collected under one unique reference number consisting of a country code, institution code, the number of the source and the page number from which the watermark is taken. Huge work has also been done to assign individual watermarks to their paper mill and papermaker of origin.

The search for watermarks on the Wasserzeichen-Informationssystem can be executed using various methods and different types of keywords. First off, motif browsing is the default system offered by the platform, similar to the ones seen already in Piccard Online and the

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78 Frauenknecht E., Stieglecker M., “WZIS – Wasserzeichen-Informationssystem: Verwaltung und Präsentation von Wasserzeichen und ihrer Metadaten”, in Duntze O., Schaßan T., Vogeler G. (hrsg.), *Kodikologie und Paläographie im digitalen Zeitalter 3 - Codicology and Palaeography in the Digital Age 3*, Books on Demand GmbH, Norderstedt, 2015

79 Maier G., Wolf C., op. cit., in Rückert P., Frauenknecht E. (hrsg.), *Wasserzeichen und Filigranologie…*, cit., p.73

Bernstein project: among a selection of motifs, the user is asked to choose the group to which the watermark probably belongs and, by exploring the tree structure, going deeper into the description of the mark to arrive to the nearest possible solution.

Searching can be also done by browsing or searching the institutions and collections present in the database divided by country, city and single archive, arriving at the specific source, or via browsing a list of names of paper makers and paper mills given in alphabetical order. An advanced search tool is also available with specific fields for the inspection of the database. In this section is also possible to search geographically with the link "Search by Map", which gives three different options: place of use, depository and paper mills. Once having selected one of these possibilities, a map opens, along with a search field for motif, time span, place and notes.

The results of each of these search methods are single watermark cards. These are well documented with the reference number, the source in which the watermark is contained, the links to the countermark and corner-mark and the references to other databases containing information on the specific mark. This information comes together with different functionalities to modify the watermark image, like the possibility to mirror it or to increase or decrease the brightness, and to save the card as a PDF or directly by printing it. An example of a single watermark card is shown in Fig. 5.

Fig. 5 - The watermark card of a lily watermark with an additional motif of shield and letters, together with all the functionalities and cross-references to the countermarks and to other databases

New possibilities for collaboration and networking between different institutions in the field of filigranology have appeared thanks to Bernstein and the WZIS, the former an aggregative platform for decentralised single databases, and the latter being a centralised collection point for many institutions. Many of the emerging projects on watermark analysis using digital methods entrust the WZIS for the collection of their data, and are therefore also indirectly published also on the Bernstein webpage.

Despite the important connections between these two projects, there are significant differences and limitations. The Bernstein portal primarily offers a metasearch for queries on decentralised databases and can therefore only provide limited functionality due to the extremely inhomogeneous data contained in the linked collections. Its prized interoperability is, in fact, compromised by the wide variety of reproduction techniques, differences in terminology and the description of data over the various databases. The idea of unifying the captions contained in each database to a common standard was not effective enough to reach the desired results: the search tool still shows some discrepancies and differences in results when using different languages or terminologies to define a motif. The wide variety of description procedures used by each institution for the cataloguing of watermarks, and the variety of in reproduction techniques (drawing, rubbing, transmitted light, beta radiography), quality, dimensions and visual aspects (e.g. colour) of images make it challenging to analyse and compare the available data. Since the uploading of these is executed locally, the quality and quantity of information is often inhomogeneous between single watermark designs. The necessity for a general revision and implementation of further data is a necessary prerequisite for the correct and useful development of this project in the future.

On the other hand, the WZIS database makes the quality and interoperability of its data its strong point: exploiting the great advantage of a centralised database system and a standardised method for the insertion of data, the database regulates the quality of uploaded watermark reproductions and information and enables faster response time. In the future, the WZIS plans to open up to new institutions and research projects, which help to broaden the horizons and enrich the database with new certified and quality information.

2.3 - *Watermarks comparison*

Watermark comparison is at the basis of filigranological research for bibliographical purposes, once achieved via long studies on printed repositories. The success of bibliographical analysis of antique handmade paper was dependent entirely on the scholar's ability to identify and distinguish the product of a single paper mould, to twin mould, and to discriminate them from the watermarks resulting from other similar mould or couple of moulds[80]. Direct contrast was accomplished using transparent paper traced with the exact size design of a watermark and superimposed on another sign, to see if they coincided in all significant points. This permitted the direct comparison of the differences between the two marks to understand if they actually came from the same mould or not. Once databases and watermark collections were moved online, the issue of quick and easy mark design research, also suitable for non-professionals, arose. In fact, as underlined in the preceding chapter, one of the main objectives of large online repositories is to help not only scholars but also a more general public, to look for similar watermark designs, for twin watermarks and mould mates. The retrieval of comparable impressions is performed in various ways: via keyword research, image query, IPH codes, pattern recognition, drawing of similar shapes etc. On the list of the IPH association, there is however no database that a user could utilise to search for similar or identical watermark designs via an uploaded image. This has been made a priority in the most recent filigranological research, as scholars are looking for a useful tool to retrieve similar signs among large collections. Watermark comparison may also be used on single manuscripts reproductions, in order to reconstruct the bibliographical history of a single source. These tasks are often quite difficult to achieve: watermark reproduction methods, as shown in Chapter 2.1, are many and different, as are the resulting images. The dissimilarity between these pictures, the type of background and the clearness of the watermark outline has been a challenging obstacle to overcome. However, some promising results have been registered, using different algorithmic methods.

Here some case studies will be presented showing different techniques to approach watermark comparison, and thus define its evolution and latest achievements.

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[80] Carter Hailey R., "The Bibliographical Analysis of Antique Laid Paper: A Method", in Hawkins A. R., *Teaching Bibliography, Textual Criticism, and Book History*, Pickering & Chatto, London, 2006, p. 151

One of the first attempts to compare and find watermarks using digital media is described in the article by Christian Rauber, Peter Tschudin and Thierry Puin[81], in which six different methods for the retrieval of images from a collection of watermarks are described. The most interesting to be analysed in this context is the comparison of similar pictures, in which the three scholars were able to use the image of a watermark to retrieve the database entry of a similar one. To do this, they developed a similarity task processing algorithm, based on a circular histogram: this element is computed around the watermark gravity centre, used as a middle point to compute the histogram, and split into 16 equivalent parts. For every quadrant, the number of pixels present is computed. Two watermarks are then similar when their respective histograms look similar. The researchers claimed that this system was quite efficient; however, the comparison works only by looking at the watermark outline, ignoring chain and laid lines, and the algorithm was trained on a very limited catalogue of marks. Because of this, Rauber et al. do not express any clear judgement about their final results.

A second important research in the field of digital watermark retrieval is described in an article by Hector Moreu Otal and Jan C. A. van der Lubbe, in which the two authors developed a system for isolation and twin watermark retrieval using the reproductions contained in the Piccard collection[82]. After having isolated the outline of the watermark from the laid lines and other noise, the image is divided into zones, counting the pixels for each sector. The system stores the information in a vectorial form, saving small details of the watermark and being able to identify similar designs. The matches are found by comparing each vector and finding the smallest Euclidean distance. The system, however, shows problems of reliability, not being able to detect and differentiate identical and similar watermarks. This is because the data is retrieved via hand-traced watermark design, which makes them imprecise and not exactly suitable for consistent comparison.

A different approach was presented by David Picard et al.[83]: starting with the idea of discarding technical watermark description as a retrieval method, due to its heavy dependence

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[81] Rauber C., Tschudin P., Puin T., "Retrieval of Images from a Library of Watermarks for Ancient Paper Identification", *Proceedings of EVA 97*, Elektronische Bildverarbeitung und Kunst, Kultur, Historie, Berlin, 1997

[82] Moreu Otal H., van der Lubbe J. C. A., "Isolation and Identification of Identical Watermarks Within Large Databases", *Elektronische Medien & Kunst, Kultur, Historie Konferenzband EVA (2008 Berlin)*, Berlin, Germany, 2008, pp. 106-112

[83] Picard D., Henn T., Dietz G., "Non-negative dictionary learning for paper watermark similarity", *50th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, 2016, pp. 130-133

on expertise in the field of filigranology. The authors developed a query based on an image-to-image search in order to find similar watermarks. The first step consists of representing watermarks as specially crafted vectors, by dividing the image into sectors and extracting information from each region. Every region is composed of the union of basic patterns, previously registered in a dictionary learned on a large set of watermark images. Similar regions of two different watermarks are given the same codes by the dictionary, thus comparing areas using the codes as a proxy. Finally, the codes are aggregated into a single vector so that the dot product simulates matching areas. This approach has led to promising results. However, it does not take into account the possibility of cross-depiction, which is the challenge of identifying the same object when it is reproduced in different ways.

The problem of cross-depiction is explored in the article by Vinaychandran Pondenkandath et alia[84], who acknowledge the fact that, in the majority of situations, watermarks repositories are composed of reproductions resulting from very different imaging methods, making it hard to use any pattern recognition technique and creating the so-called "Cross-Depiction Problem"[85]. Using the WZIS dataset, the scholars both developed a system for classifying the watermark (given an image, the correct label is returned) and for matching similarities between images. The technique developed is based on the use of deep learning, specifically convolutional neural networks, capable of comparing watermark reproductions of very different kinds, like rubbing, thermography, radiography or photography. The system results are effective for both classification and similarity-matching tasks, proving to be a turning point in the application of deep learning in the field of watermark recognition. Further developments of the same method are described in the 2020 article by Pondenkandath et al.[86].

Looking for a similar technique for watermark recognition and matching, the study by Shen et al.[87] approaches the research using a convolutional neural network. The paper begins with the

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[84] Pondenkandath V. et al., "Identifying Cross-Depicted Historical Motifs", *16th International Conference on Frontiers in Handwriting Recognition (ICFHR)*, 2018, pp. 333-338

[85] For a description of the Cross-Depiction Problem in artworks: Cai H. et al., *The Cross-Depiction Problem: Computer Vision Algorithms for Recognising Objects in Artwork and in Photographs,* 2015, arXiv preprint arXiv:1505.00110

[86] Pondenkandath V. et al., "Cross-Depicted Historical Motif Categorization and Retrieval with Deep Learning", *Journal of Imaging*, Vol. 6, No. 71, 2020

[87] Shen X. et al., "Large-Scale Historical Watermark Recognition: dataset and a new consistency-based approach", *25th International Conference on Pattern Recognition (ICPR)*, Milan, Italy, 2021, pp. 6810-6817

retrieval of watermarks via back-lit photography from documents collected in the Minutier Central des Notaires de Paris, the archive responsible for preserving notarial documents from the 15th until the 20th century. This type of collection was chosen because of the abundance of similar watermark designs: in fact, notarial offices used (and still do) large quantities of paper, which led to the collections of many samples of the same type of sheets, perfect for training the algorithm for image matching and recognition. The further addition of the reproductions contained in the Briquet catalogue of watermarks built up the final and complete dataset, making it interesting also from the point of view of cross-depiction. After training the network, a global similarity score is computed and then refined by the computation of a local similarity score. Results show some limitations in comparison and matching of extremely similar watermarks since the dataset is probably characterised by a high presence of extremely similar watermarks, making it difficult for the system to recognise the little differences. Recently, this tool has also begun being developed as a web application[88].

Based on the use of VGG Image Search Engine (VISE), developed by the University of Oxford's Visual Geometry Group, the project carried out by the National Archives[89] (previously described in this work in Subchapter 2.1.6) makes a step toward computer vision algorithms. The method is strong in comparing images of different sizes and rotations, using SIFT features, which are visible differences in texture and contrast between photos. The system proves to be very fast but limited at cross-depiction analysis.

One of the latest studies in watermark comparison was described and published by Richard Johnson, William Sethares, and Margaret Holben Ellis, analysing the paper structure of Rembrandt's drawings[90]. Their method is based on two computational tools that are used to build an overlay of the two watermarks for comparison and matching (but not searching): the first is a point-and-click tool, called "watermarkPointMarker", which permits the user to mark a series of points on the pair of watermarks reproductions; after having manually pointed out the spots for comparison, the resulting data files are moved into a different software, "visualizeOverlays", which checks each marking on the two images and aligns them. The

[88] Bounou O. et al., "A Web Application for Watermark Recognition", *Journal of Data Mining and Digital Humanities*, 2020

[89] Pereira Pardo L., Bergel G., op. cit.

[90] Johnson Jr. C., Sethares W. A. R., Holben Ellis M., "Overlay Videos for Quick and Accurate Watermark Identification, Comparison, and Matching Creating and Using Overlay Videos", *Journal of Historians of Netherlandish Art*, Vol. 13, No. 2, 2021

more points are marked, the less the error in the alignment. The final goal of this procedure is to create a loop video in which the images of one and the other watermark alternate, fading and reappearing continuously. This process helps the scholar to directly notice the differences between the two images. One of the main advantages of this method is the ability to compare images regardless of their orientation, scale or resolution. The limitations are instead the long process of manually placing the points in each watermark image, and there is still the need for a human evaluation of the result, as there is no computed ratio giving a measure of the differences between the two watermarks. Rather the subjective opinion of the scholar is responsible for telling if the two watermarks are actually identical or not. This kind of research is then applicable only to very small datasets since the time-consuming operations of marking and comparison would be impossible to perform on a large scale.

The method here described was further applied in the study by Abigail Slawik et al.[91], in which was also added a program to measure chain line intervals, the "ChainLineMarker". Another research approaching watermark image comparison via overlying videos is the LEOcode project[92], in which the same three scholars Richard Johnson, William Sethares, and Margaret Holben Ellis, study the Codex Leicester and Codex Arundel by Leonardo da Vinci in order to find matching mould-mates and twin watermarks.

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91 Slawik A. et al., "User-Friendly Software for Identifying Moldmates and Twins in Antique Laid Paper: Case Study of a Disbound Blank Book", *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies*, Vol. 7, No. 2, Fall 2022, pp. 341-360

92 Holben Ellis M., Sethares W. A., Johnson Jr. C. R., "A Powerful Tool for Paper Studies: The Computational Coding of Watermarked Papers in Leonardo's Codex Leicester and Codex Arundel", *The Quarterly: The Review of the British Association of Paper Historians*, No. 119, July 2021, pp. 1-18. For further information: https://leocode.org/, LEOcode, *Project website*. Last visited 02/08/2023

3 - The DRACMarkS Project

3.1 - Introduction

DRACMarkS (Digitisation, Recognition, and Automated Clustering of Watermarks in the Music Manuscripts of Franz Schubert)[1] is an interdisciplinary project working in the intersection between musicology, filigranology and digital humanities. Promoted by the Austrian Academy of Sciences (ÖAW - Österreichisce Akademie der Wissenschaften) the project intends to digitise and catalogue the watermarks contained in the original music manuscripts written by the Austrian composer Franz Schubert, and to compare them via machine learning and signal processing methods. The program aims to enrich the future database contained in the Schubert Digital website and to limit the approximate dating of some of the author's manuscripts. The main steps of the project consist of the use of a thermographic system for the reproduction of watermarks, their description and cataloguing using an XML file structure according to the guidelines of the Music Encoding Initiative (MEI) and methods inspired by fingerprint recognition software for motif and twin marks matching.

In this chapter, a brief introduction to the relationship between musicology and filigranology will be first outlined. The project will be then described in detail, focussing on the equipment used, the workflow and the expected results. Finally, limitations and further developments will be explored.

3.1.1 - Watermarks and musicology: an overview

As in other disciplines, the relationship between watermarks and musicology is primarily based on the use of these signs for dating and the study of paper origin and dating. On the basis of the discoveries made using watermarks, it is possible to describe the reception and distribution of certain music pieces, to study the genesis of a music work and its creation process, to identify anonymous fragments and to explore the story of a music genre and its evolution.

[1] https://www.oeaw.ac.at/acdh/projects/schubert-watermarks, Austrian Academy of Sciences, *DRACMarkS project*. Last visited 13/08/2023

The first research combining filigranology and musicology dates back to the 19th century. An untimely example is represented by the collector Aloys Fuchs, who with the aid of paper analysis had tried to date a Mozart autograph. In the second half of the 19th century, it was Friedrich Chrysander who referenced watermarks in his biography of Georg Friedrich Handel[2]. In this case, the combination of different complementary methods like filigranology and the study of Handel's calligraphy was the foundation of a concrete analysis.

The proper beginning of studies in musicology with the aid of watermarks, however, is the research of Philipp Spitta about Johann Sebastian Bach's manuscripts, in which watermarks were used to determine the chronology of Bach's works[3]. Due to the scarce knowledge and lack of theory about filigranology at the end of 19th century, Spitta committed numerous mistakes. This led to a general scepticism about watermark studies applied to musicology, and the union between the two disciplines went through a period of strong resistance. The real turning point began in the 1950s, with the studies promoted by Theodor and Wisso Weiß again on Bach's compositions, and continued until the 1970s, when music scholars completely embraced the utility of paper studies[4]. It was Allan Tyson who was actually responsible for a significant step forward in the theoretical determination of watermarks in musicological studies thanks, in particular, to his solid analysis of the felt and mould side and the determination of identical and similar watermarks. Tyson was the author of revolutionary works about Ludwig van Beethoven[5] in which, with the support of watermark evidence, he suggested the evolution of the composer's sketchbooks, and how they had been damaged and modified over time. In the appendix of one of his articles entitled "The Problem of Beethoven's 'First' 'Leonore' Overture"[6], Tyson states the "Ground Rules for the Description of Watermarks". These take into consideration the clue of twin watermarks suggested by Alan H. Stevenson, the distinction between mould and felt side and the consistency in stating the preferred one for looking at paper sheets, the way to enumerate the four quadrants in which

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[2] Chrysander F., *G. F. Händel*, Bd. 1, Breitkopf und Härtel, Leipzig, 1858

[3] Spitta P., *Johann Sebastian Bach*, Bd. 2, Breikopf und Härtel, Leipzig, 1880, p. 775

[4] Hudson F., "Musicology and Paper Study - A Survey and Evaluation", in Spector S. (edited by), *Essays in Paper Analysis*, Folger Shakespeare Library, Washington-London, 1986, p. 43

[5] Tyson A., Johnson D., "Reconstructing Beethoven's Sketchbooks", *Journal of the American Musicological Society*, Vol. 25, No. 2 1972, pp. 137-156

[6] Tyson A., "The Problem of Beethoven's 'First' 'Leonore' Overture", *Journal of the American Musicological Society*, Vol. 28, No. 2, 1975, pp. 292-334

the original sheet is folded, and the best and most precise way to describe and reference watermarks. Tyson's work also includes studies on Amadeus Mozart's compositions[7], applying the techniques used previously with Beethoven autographs in the study of Mozart's manuscripts.

Admiring the methods used by Tyson, the American scholar Robert Winter applies the same techniques to the analysis of Franz Schubert's sources. In his article "Schubert's Undated Works: A New Chronology"[8], Winter lists all the dubiously or undated manuscripts in Schubert's work, dismantling some assumptions thanks to the study of watermarks. It was in this way possible to date a part of the chronologically unclear works and to re-date some others which were incorrectly positioned in time. Further observations were implemented and deepened in the article "Paper studies and the future of Schubert research"[9], in which again Winter stresses the importance of paper studies in order to settle a defined and well-established chronology of Schubert's works.

Despite this long tradition, the potential of watermark analysis in musicology has not been exploited completely. The determination of a series of common standards and parameters for the analysis of watermarks in a musicological context, together with broader research on various composers instead of a narrow focus on specific sources, would open up new interesting perspectives. As already vastly described in precedent chapters, the use of reliable and scientific methods for watermark reproduction is also fundamental, in order to achieve satisfying results in terms of image quality and consequent analysis. The essay "Watermarks and Musicology" by Jan le Rue[10] represents a first attempt at a complete and concrete theoretical basis for filigranology applied to musicology. In the article, le Rue gives a clear explanation and guidance on technical problems related to watermark description, recording and use for dating manuscripts. Le Rue does not miss the opportunity to notice the great help

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[7] Tyson A., "New Light on Mozart's 'Prussian' Quartets", *The Musical Times*, No. 116. 1975, pp. 126-130; Tyson A., "'La Clemeneza di Tito' and its Chronology", *The Musical Times*, No. 116. 1975, pp. 221-227

[8] Winter R., "Schubert's Undated Works: A New Chronology", *The Musical Times*, Vol. 119, No. 1624, 1978, pp. 498-500

[9] Winter R. "Paper studies and the future of Schubert research", in Badura-Soka E., Branscome P. (eds.), *Schubert Studies. Problems of Style and Chronology*, Cambridge University Press, Cambridge, 1982

[10] Rue J. le, "Watermarks and Musicology", *The Journal of Musicology*, Vol. 18, No. 2, 2001, pp. 313-343

that filigranology can give to anyone dealing with undated manuscripts, underlining the shortcuts and sped-up processes that the application of these methodologies offers.

The latest developments in paper studies involving the use of digital media and new technologies have also touched the world of musicology. An example is the cataloguing and digitisation of watermarks in music manuscripts of the Bayerische Staatsbibliotek up to the end of the 17th century[11]. Supported by the German Research Foundation (DFG) developed between 2018 and 2020, watermarks in music manuscripts have been digitised using thermographic technology, made available online and integrated into the WZIS database. Another project regarding the digital documentation of watermarks contained in music manuscripts has been developed in the context of the Berlin Staatsbibliothek - Preußischer Kulturbesitz under the name of Project KoFIM[12]. The project aims to reproduce watermarks conserved in the Library using a thermographic camera and upload the results both on WZIS and on RISM (Répertoire International des Sources Musicales). Paper and Copyists in Viennese Opera Scores (P&C)[13], is a further project which inspects the Habsburg collection opera scores in Vienna. These manuscripts consist of copies of original works by different composers which were created by professional copyists. The study of watermarks contained in these papers helps to trace their chronological collocation. For this reason, the research project aims to complete an accurate and accessible catalogue of watermarks to date these sources. This is done using back-lit pictures of the manuscripts and image subtraction to reach a satisfying and objective representation of the watermarks. Once ended, the results will be published on the Bernstein Portal.

[11] www.bsb-muenchen.de, Bayerische Staatsbibliotek, *Cataloguing and digitisation of the watermarks in music manuscripts of the Bayerische Staatsbibliothek up to the end of the XVII century*. Last visited 14/08/2023

[12] Eckhardt W., "Digitale Dokumentation von Wasserzeichen in Musikhandschriften im Rahmen des Projekts KoFIM", in Eckhardt W. et alia (hrsg.), *Wasserzeichen, Schreiber, Provenienzen: neue Methoden der Erforschung und Erschliessung von Kulturgut im digitalen Zeitalter: zwischen wissenschaftlicher Spezialdisziplin und catalog enrichment*, Vittorio Klostermann, Frankfurt am Main, 2016, p. 168-195; staatsbibliothek-berlin.de/en/about-the-library/departments/music/projects/dfg-projekt-kofim-berlin, Staatsbibliiothek Berlin, *DFG-Project KoFIM Berlin (Music Research and Information Competence Centre)*. Last visited 16/08/2023

[13] www.mdw.ac.at, Paper and Copyists in Viennese Opera Scores, *Home*. Last Visited 28/09/2023

3.1.2 - The DRACMarkS project

At the intersection between watermark research, musicology and digital humanities the project DRACMarkS[14] is one of the latest and still ongoing programs in the field, started in September 2021 and will continue until August 2024. Housed in the Austrian Academy of Sciences (ÖAW), specifically at the Austrian Centre for Digital Humanities and Cultural Heritage (ACDH-CH), the project was supported by the funding program Heritage Science Austria. This is directly financed by the National Foundation for Research, Technology and Development of Austria, aiming to promote interdisciplinary projects in the field of heritage science and humanities. The project concerns the digitisation, classification and comparison of watermarks contained in the autograph manuscripts of Franz Schubert.

Schubert was an Austrian composer of the early Romantic era, who was born in Vienna in 1797 and died in the same city in 1828. His oeuvre encompassed almost all contemporary music genres (in particular German Lieder, symphony, opera and sacred, piano and chamber music) and marks a milestone of the early 19th century and in music history in general.

The cataloguing of these manuscripts began in the 1960s, with the foundation of the Viennese Research Group of the New Schubert Edition (Neue Schubert Ausgabe - NSE)[15], appointed to create a New Schubert Edition, a collection of critical reports analysing each of the relevant music manuscripts produced by Schubert. Since 1978, it has been financed by the Federal Republic of Germany, the State of Baden-Württemberg, the Republic of Austria, the City of Vienna, and the Austrian Academy of Sciences. Being a “scholarly-critical edition”, The NSE considers all accessible sources, not just noting their various interpretations but also making an effort to retrace the development of each work. This association of scholars was able to collect more than 1,300 tracings of watermarks in Schubert’s works. Since 2012, the NSE has been working on the widest digital collection of Schubert autographs, the Schubert Online database[16]. On this website it is possible to virtually access the original manuscripts and the watermark tracings executed by the NSE, putting together those autograph scores which are

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[14] The project has been introduced in the paper: Gulewycz P. et alia, “Watermarks and Where to Find Them: Digitisation, Recognition, and Automated Clustering of Watermarks in the Music Manuscripts of Franz Schubert”, in Ang A. L., Bain J., Weigl D. M., *Music Encoding Conference 2022 Proceedings*, Dalhousie University, Halifax, Canada, 2023, pp. 80-88

[15] https://schubert-ausgabe.de/en/, Neue Schubert Ausgabe, *Homepage*. Last visited 16/08/2023

[16] schubert-online.at, Schubert Online, *Homepage*, Last visited 16/08/2023

physically collected in different places. Recently, the NSA has been working on a newly designed database called Schubert Digital, which will gradually substitute Schubert-Online, creating a strong base for future research on Schubert's works and their transmission.

It is here that the DRACMarkS project comes into play: the intention is to exchange the old tracings for new digital reproductions, which will be described, compared and stored in the new Schubert Digital platform and in the WZIS database. More specifically, thanks to the use of a thermographic imaging system equipped with an infrared camera it will be possible to record the watermarks contained in Schubert autographs at the Österreichische Nationalbibliothek and Wienbibliothek im Rathaus. The Wienbibliothek alone holds 492 music manuscripts by Schubert, allowing the DRACMarkS team to work in their archive and use the thermographic system on their premises. The process of digitisation involves also the use of XML files structured according to the guidelines of the Music Encoding Initiative (MEI), optimised to archive information about the watermark and its appearance. In a further step, the images will be compared and matched using a methodology based on points of interest. This technique, similar to the one used in fingerprint recognition, will help scholars to identify similar and identical watermarks, supporting further research on Schubert autographs. The final idea is to then upload these images onto the future Schubert Digital website, and create a specific type of visualisation tool which will allow the visualisation of the scanned manuscript together with the image of its internal structure, including watermarks displayed following IIIF standards.

Apart from using watermarks to review Schubert's manuscript chronology, other important information will be extrapolated from these digitised images. During the process of watermark recognition, in fact, the project team plans to retrace the origin of each paper used by the Austrian composer. This will help to reconstruct the paper trade routes and development of the paper industry in the Austro-Hungarian Empire, by following the pathways from the paper mill of origin to the final consumer.

3.2 - Steps of digitisation

In this chapter, the first phase of the digitisation process will be described, consisting of a first analysis of source manuscripts one by one and page by page, of the metadata registration inside an especially created XML file, and of the digitisation via a thermographic system. Just after the image acquisition, the first quality control and correction of the resulting image is accomplished. Before the detailed description of each of these steps, an overview of the equipment used for digitisation, including the thermographic camera and the XML file, will be reported.

3.2.1 - The tools and equipment for the digitisation phase

In this first phase of the project dealing with the description and digitisation of watermarks and paper, two fundamental tools are employed: the XML file structured according to the MEI standard, and the thermographic system.

As will be described more precisely in the next Chapter 3.2.2, before starting with the actual imaging of watermarks, a first inspection of the paper is performed. It is in this phase of the process that the XML file is first utilised. It is designed as a fillable form in which general information and description of the watermark appearance are entered. Specifically, the XML file is encoded following the MEI, an encoding standard for the transcription and a description of musical documents in a machine-readable structure.

The use of MEI for the description of watermarks is something new and continuously developing. In her article “A TEI Customisation for Paper and Watermarks Descriptions”, Ermenegilda Müller has worked with the Text Encoding Initiative (TEI) encoding standard, used for the digital description of text-bearing objects[17], applying it to the study of watermarks[18]. The TEI might be used to describe paper and watermarks by using a specific XML element. However, this does not take into consideration all the specific aspects essential for their detailed and useful analysis. Müller then proposes a customised extension adapted to IPH standards, enabling the recording of more standardised information easily accessible online, facilitating the exchange between different scholars and fields of study. Furthermore, data encoded in XML and gathered into a database can be mined, exporting information useful to determine the origin and circulation of paper and watermarks.

[17] TEI works similarly to MEI, the basic difference between them is the focus of their description: TEI works with textual sources, MEI deals with musical sources.

[18] Müller E., “A TEI Customization for Paper and Watermarks Descriptions”, *Digital Medievalist*, Vol. 13, No. 1, 2020, pp. 1-24

DRACMarkS project has then decided to use XML files for the archiving of watermark information and a link to the thermograms. The creation of a dedicated file for the encoding of watermarks has been and still is an important part of the project, with the team working on a standardised way to describe them in MEI[19]. The work done at the ÖAW will be then discussed and implemented with the help of the MEI community. For the standardised description of the watermarks, the categories promoted by the Bernstein project are used, in order to ensure future findability inside online databases.

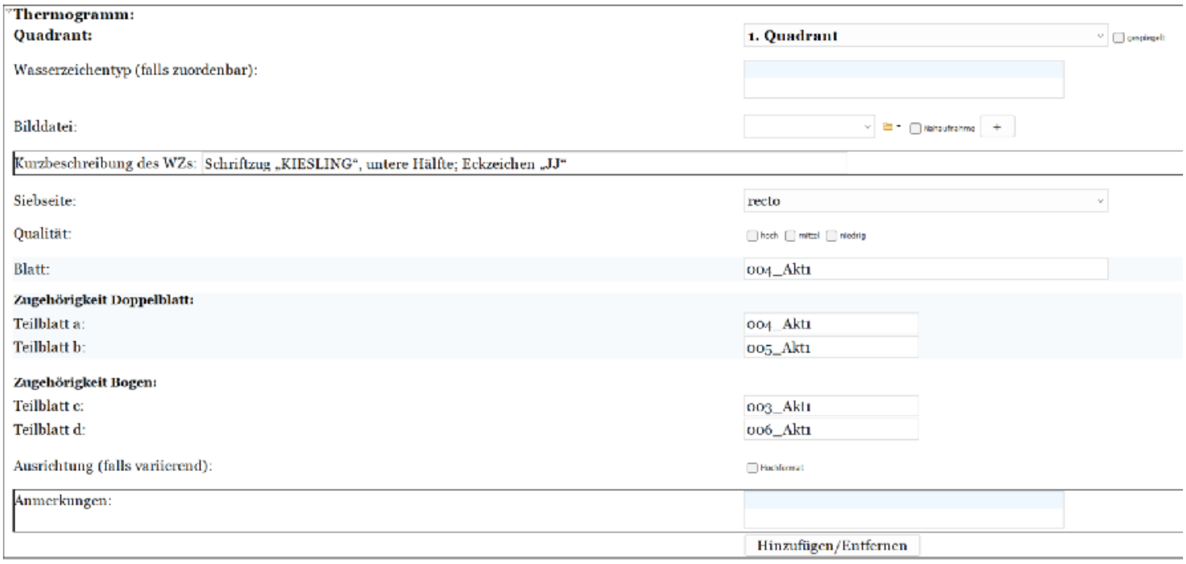

Fig. 6 - XML file encoded in MEI, here visible as user-friendly interface due to the embedding of a CSS file

Following the project's workflow, for each Schubert manuscript, a single file is created, and structured in order to include all the necessary information for fast recognition of each watermark. By embedding a CSS file (Fig. 6) the XML structure can be accessed in a user-friendly interface in the so-called Author Mode of the Oxygen XML Editor, which is a commonly used proprietary software in DH projects. This has helped to hide the crude XML encoding to make the compilation faster and more intuitive. The creation of selectable and tickable options, drop-down menus and text suggestions helps the user to rapidly fill up each field. The use of such structured and pre-populated files for the archiving of information also helps the easy finding of any data with a simple search.

The second step of digitisation employs a thermographic system, an infrared camera sensitive to thermal radiation. The choice of using a thermographic system for the reproduction of the

[19] Gulewycz P. et alia, op. cit, p. 86

paper's internal structure is the result of a detailed decision process. In experiments by Peter Meinlschmidt and other scholars at the Staatsbibliothek Berlin,[20] this system revealed to be particularly useful for reproducing not only the watermark but the entire inner structure of the paper manuscripts. Other methods were analysed by the members of the DRACMarkS project: beta-radiography, one of the most acclaimed technologies for watermark reproduction, was discarded because of the difficulty of retrieving the basic material needed for it to work; the idea of using transmitted light photography with additional image subtraction seemed to be a good alternative, however not practicable in the case of the DRACMarkS project, as the quality of paper needs to be high in order to reach satisfying results using this method. Furthermore, as already described in Chapter 2.1.2, the writing ink, even when the most advanced methodologies for image subtraction are used, remains slightly visible. Thermography was then chosen as the fastest and easiest way to digitise watermarks. Furthermore, in comparison to radiographic methods, thermography is much more cost-effective, involves fewer health risks for the operator and takes less time to create an image.

For the digitisation of watermarks in Schubert manuscripts, the team of the DRACMarkS project has chosen to collaborate with the Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut (WKI). The WKI team was able to assemble a portable version of a thermographic system, in order to make it easier to transport it from one library to another[21]. The system uses the infrared camera IRCAM Taurus 327k SM[22]. This camera is equipped with a Mercury Cadmium Telluride (also known as MCT or HgCdTe) detector, a type of thermal camera sensor tunable in the Mid-Wave Infrared (MWIR) range of 1.5µm - 5.5µm, highly sensitive to temperature differences. The IRCAM Taurus is also provided with a couple of lenses of different focal lengths, 25mm and 50mm, which are easily interchangeable by rotating a disk in front of the camera. The lenses are used, respectively, to take a picture of the entire page and to shoot close-ups of the watermarks alone. The camera, slightly inclined, is placed on a vertical carriage and it is adjustable up-and-down and right and left with a lever

[20] Meinlschmidt P., Immel H., "Digitale Dokumentation von Wasserzeichen mittels Thermographie", in Eckhardt W. et alia (hrsg.), *Wasserzeichen, Schreiber, Provenienzen: neue Methoden der Erforschung und Erschliessung von Kulturgut im digitalen Zeitalter: zwischen wissenschaftlicher Spezialdisziplin und catalog enrichment*, Vittorio Klostermann, Frankfurt am Main, 2016, pp. 197-217

[21] Gulewycz P. et alia, op. cit, p. 84

[22] All the technical information about the camera system is extracted from: Fraunhofer WIKI, *Watermark Imager - Wasserzeichenerkennung mit Thermographie - Benutzerhandbuch*, Version 7.6, 1/8/2019

positioned on the back of the device. In front of it, a copper plate, movable horizontally and vertically and heatable up to 36/37°C, is installed in an inclined position, in order to favour the right laying of the analysed source aligned with the camera. In order to avoid direct contact between the manuscripts and the heat source, the DRACMarkS team, inspired by the work of Meinlschmidt, decided to create a passepartout, a plastic frame of about 1 cm thick covered by a layer of cling film. The passepartout is placed on the copper plate and held with three small magnets, which guarantee a good and stable positioning. Before coming up with the idea of covering the passepartout with kitchen cling film, other materials were taken into consideration: these had to be transparent and insensitive to heat. In this way, the chosen material could support the manuscript without notching the resulting image. Glass and aerogel were studied to understand their suitability: glass was not efficient enough in letting thermal radiation pass to be considered, and aerogel, a synthetic ultralight material, was too expensive. After some research, the idea of the cling film seemed to respect all the prerequisites, being cheap, easy to retrieve and, in case of damage, rapidly replaceable. To shoot the thermograms, a pedal board is attached to the camera and the image is triggered once the operator presses the pedal. The image is then transmitted to a connected computer in which, by using compatible software, a first adjustment of resulting thermograms is made.
The thermographic system here described is shown in Fig. 7.

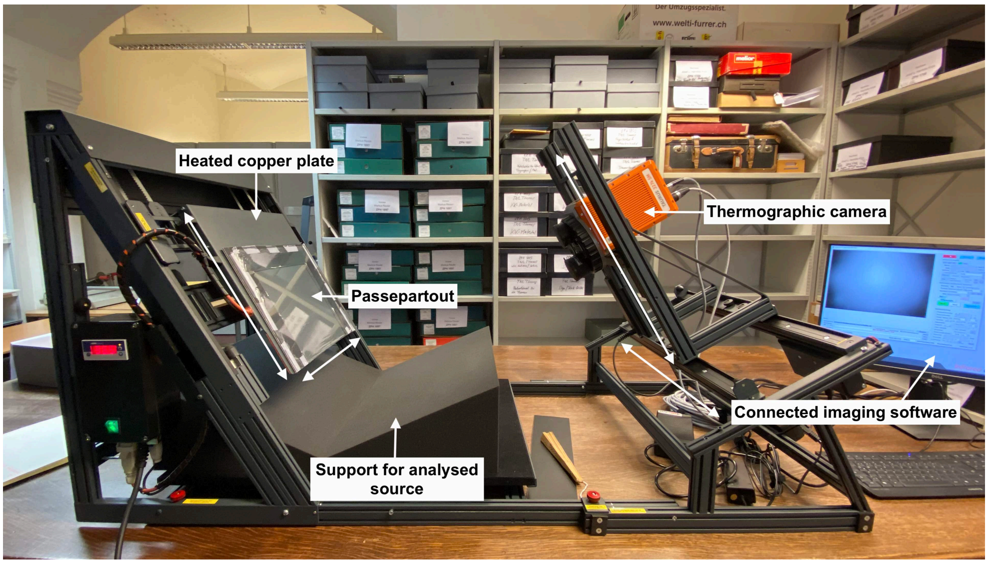

Fig. 7 - The thermographic system used in the DRACMarkS project and installed at the Vienna City Library

3.2.2 - Manual analysis of the source and recording in MEI file

The first phase of the workflow regarding the thermographic reproduction of watermarks in the DRACMarckS project consists of a detailed analysis of every single leaf composing the manuscript and subsequent registration of its characteristics in the XML fillable form.

Before continuing with the description of watermarks and paper manual analysis, some specific characteristics of music paper have to be kept in mind. First off, the bulk of 18th and 19th century music manuscripts use oblong-format paper (apart from Germany, in which the upright format was more common), which is created by folding a complete sheet in half in the short dimension, then folding and cutting it in half in the long dimension. The resulting four leaves[23] are called of "quarto" format. In an oblong manuscript, one half of the mark will often be found centred in the top margin and the second half (inverted) in a similar location on the subsequent page[24]. In these documents, the watermark and countermark are typically centred in the two halves of the sheet, as seen in Fig. 8.

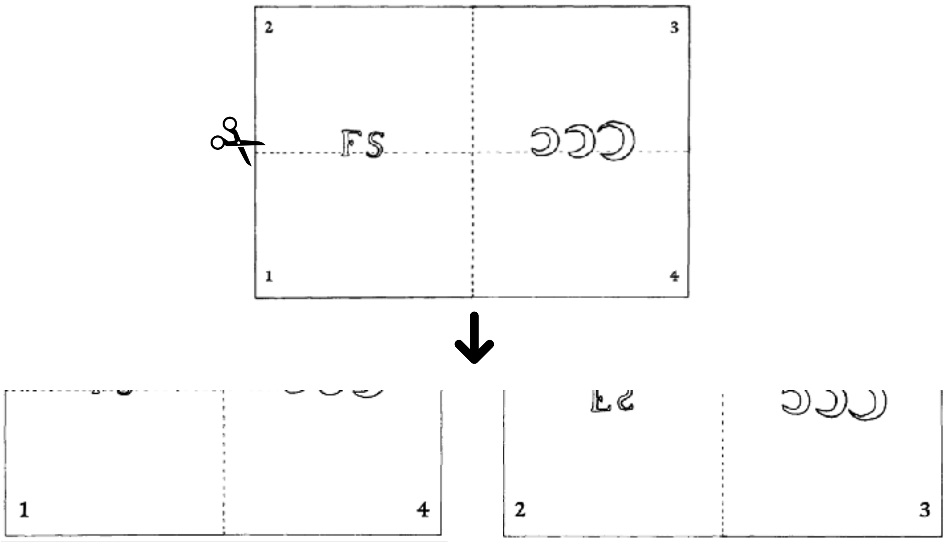

Fig. 8 - The sheet of paper is folded two times into a quarto format. The two halves are then cut and four leaves are created

Once the two halves were separated, they were normally bound together in order to create a quire. The sequence of the leaves in the newly created booklet will be 1-2-3-4. In this way, the watermark will be divided in the four resulting leaves, and each of them will only have a partial view of the watermark design. One of the first things to have in mind while looking at

[23] A leaf is typically a sheet of paper, a page is instead one of the two sides of a leaf.

[24] Rue J. le, op. cit., pp. 314

music paper is that, in order to recreate the original sheet, the four single leaves have to be found and rematched, first by recomposing the 1-4 and 2-3 leaves couples and then looking for the missing upper or lower part of the watermark. Only in this way the original sheet will be complete and usable for further analysis.

Having said this, the analysis of the manuscript begins with the annotation of the manuscript archiving number (signature) inside the XML form. The first leaf of the manuscript is then associated with the other corresponding leaf in the binding (e.g. 1-4 or 2-3) and marked inside the specific slot in the MEI interface. Then, using a flashlight, each leaf is inspected manually to look for the watermark appearance, paper structure and felt and mould side. First off, the flashlight is positioned at a sharp angle on the page in order to inspect the paper surface. In this way, it is possible to detect the mould side thanks to the indentations left by the sieve during the process of paper creation and visible when light strikes the paper at an acute angle. The sieve side is then determined and assigned to the "recto" (front side), or verso "verso" (back side) of the page: if the indentations are stronger on the recto side of the page, then the recto side of the page is the mould side. If the indentations are stronger on the verso side of the page, then the verso side of the page is the mould side. This information will be then entered in the specific field of the XML form. After that, again using a flashlight, the watermarks are inspected, and a short description of its appearance based on Bernstein standards is included in the XML file. As explained before, for the majority of the time the watermark will not be complete but fragmented so that only its lower or upper part is visible in the single leaf. It is then documented which part of the watermark (lower or upper) is visible in the leaf that is being analysed along with a short description.

After having inserted all the useful information into the specific fields in the XML form, the successive leaf is examined, following the same steps as described here. After having accurately inspected all the leaves of the manuscript and having registered them in the file, the digitisation process using the thermographic camera begins.

3.2.3 - Thermograms

The central phase of the digitisation process consists of the creation of the thermograms of each leaf. First off, the camera and the copper plate are turned on around 30 minutes before use, so that each of them reaches the right temperature for the best resulting images. In particular, the copper plate needs to reach the temperature of around 36/37°C, the camera instead needs time to cool down to the right operating temperature. After that, the Watermark Imaging Software is opened too, and the Live Mode is turned on. Before starting with the actual thermograms, the reference parameters of the camera need to be set: a metallic circular slab attached to black felt is placed in front of the lens at room temperature. A first "cool" reference image (Ref1) is then triggered. The second image needs instead to be set on copper plate temperature. The metallic slab is then heated up by touching the plate and positioned in front of the camera lens to produce the "hot" image (Ref2). The program automatically subtracts the two images and corrects any inhomogeneity in the visualisation. These settings are necessary for the correct functioning of the camera, similar to what is done automatically in any photographic camera. The system is then ready to produce thermographic images.

Using the live mode of the software, it is possible to visualise directly what the camera is focussing on. Since the camera is not able to frame the entire leaf in one shot, two images, one of the bottom part (Position 1) and one of the top part (Position 2) of the leaf, are recorded. The manuscript is placed on the specific support, and the first leaf is lifted in order to be correctly positioned and frame the page at Position 1. In this phase also the position of the passepartout is checked, to be sure that it is not visible in the shot. The images are captured in a sequence of a determined number of frames each second. In the Watermark Imaging Software, it is possible to pre-set the number of frames captured by the camera in one shot, normally set to 100 frames, which are produced in 2 seconds. The results are a series of thermograms, from which the best-looking image can be chosen. As an alternative, the software can also create a median or mean image, which is made of the 100 frames of the sequence combined. However, the DRACMarkS team chose to use the e best-quality frame, as the first frame of a sequence is usually the best one.

After having positioned the camera in the right spot, the system is ready to shoot. In order to make the thermogram as clear as possible, a fan is used in order to cool down the paper before its exposure to the copper plate. This step is fundamental for the success of the final image: in fact, the longer the paper is exposed to thermal radiation, the worse the results of the images get. Additionally, when the sheet is left for more than a few seconds on the copper plate, ink on the manuscript may become visible in the images. In these cases, the thermogram needs to

Fig. 9 - The manuscript is positioned on the copper plate ready to be reproduced by the thermographic camera.

be repeated. Just after having cooled the page, the manuscript is left lying on the copper plate and the image is triggered using the specific pedal on the board (Fig. 9).

The manuscript lies on an adjustable book cradle and only the single page to be recorded is positioned over the copper plate for the moment needed. The mechanical stress is minimised by using foam support, well-suited for the gentle digitisation of valuable inventory. At this moment, the camera captures a series of images in the range of a few seconds and transmits them to the connected PC. The plate emits infrared radiation, which is passed through the paper and is absorbed differently depending on the sheet's thickness and density (see Chapter 2.1.5). The camera captures these variances, resulting in a thermographic image visible in the software page in which the thinnest parts of the paper, such as the watermark and other aspects of the leaf's structure, are seen as dark lines against a lighter background (Fig. 10).

The Watermark Imaging Software is used to first check the quality of the resulting images. This is one of the greatest advantages of the use of the thermographic camera, allowing the user to directly check the shot images and repeat the process at any moment on the occasions in which the resulting thermograms are not of the desired quality. Among the different frames shot by the camera, the user can choose the best-looking one. Once the right image is collected, the software is used to correct its exposure and sharpness. Furthermore, since lenses produce a certain degree of distortion, the image is dewarped and flattened. The image data is then saved in two formats, MatLab (.mat, a raw file used in the further steps of image stitching and watermarks reconstruction) and PNG. The file name will be composed of the manuscript signature (e.g. MHc-12), the page number (e.g. Bl. 7 = Page 7), and the part of the page registered (1 if the image is of pos.1, 2 for image of pos. 2). The process is repeated in the same way for recording the second leaf image (Position 2, in which the camera is moved to frame correctly the upper part of the page) and again for each page of the manuscript.

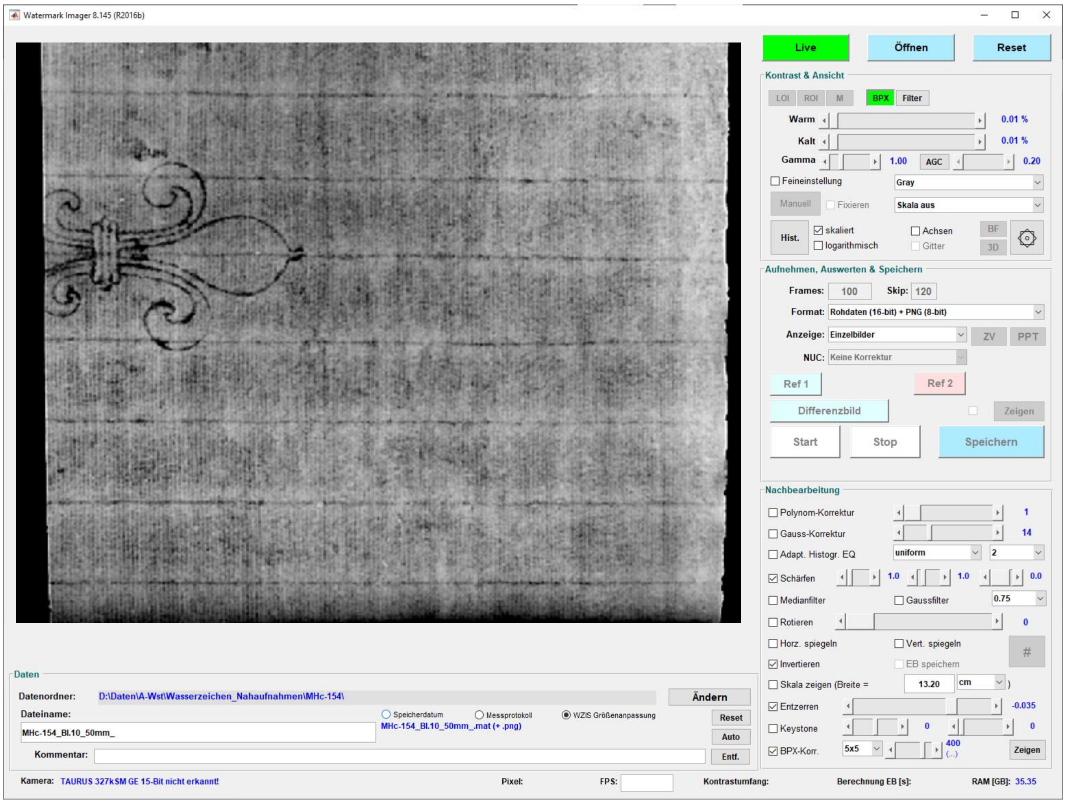

Fig. 10 - The Watermark Imaging Software showing the thermogram of the lower half of a single manuscript leaf
Source: MHc-12 - D 982 “Entwürfe für eine Oper”, Bl.7

When all the pairs of thermograms are reproduced and saved correctly, the thermographic camera is set for the imaging of watermark closeups. In this second phase, the user checks one by one the just-made images, looking for the best watermarks: the sharpest, most clear and most suitable for further comparison. In order to shoot close-up images, the lens of the camera is changed from 25mm to 50mm. The watermark is then centred in the camera frame and captured. The imaging process and the subsequent phases of image correction of these thermograms are complementary to the ones already described for the entire-page pictures.

The results are close-up images of the chosen watermarks, which are then directly corrected and modified on the Watermark Imaging Software. In the case of close-ups, dewarping is not applied directly by the software but done later using an algorithm specifically encoded by the team. Images are then saved in the double format .mat plus .png and stored together with the other manuscripts reproductions.

3.3 - Stitching of images and comparison for twin watermarks retrieval

Once all the images of each manuscript leaf are created and stored, watermark reproductions are passed to the subsequent phase. Before moving to the actual image matching, a further step is needed to make watermark reproductions useful for effective comparison.

As just explained in the previous chapter, the 25mm lens and the camera setting are not able to frame the entire manuscript page in one shot: two images are therefore produced, one of the bottom part of the page (Position 1) and another of its top part (Position 2). The idea in this stage of the project is to stitch together the two images of Pos. 1 and Pos. 2 and reconstruct the original leaf. This is done by using an algorithm programmed in GNU Octave, a software application compatible with MATLAB. Images of Pos. 1 and Pos. 2, handled in their .mat format, are uploaded in the algorithm and pixel errors are corrected. Background and the dewarping effect added to the image during its first check in the Watermark Imaging System are removed. The merging is then executed, with the algorithm capable of automatically recognising the leaf margins and stitching the two images. It can happen that, due to small movements during the thermographic procedure, the rotation of the manuscript is slightly different in the two images. This can compromise the functioning of the algorithm and require a manual intervention.

After having reconstructed every single page, a further step needs to be accomplished before the actual image-matching phase. In fact, the original sheet of paper, composed of the four single leaves, has to be reconstructed. Only in this way, it will be possible to have a complete vision of the watermarks present and use them for further matching with other similar designs. This process is now done manually since high accuracy is needed to match chain lines perfectly[25]. The procedure begins with the setting of reference points along the wire lines and the cutting of irrelevant areas. The positioning of the two images is corrected and repaired. A final check of the merged pages is completed. The two thermograms might not always perfectly merge, even though the two leaves are evidently part of the same original

[25] However, the project hopes to automatise it using comparison between mesh imprints.

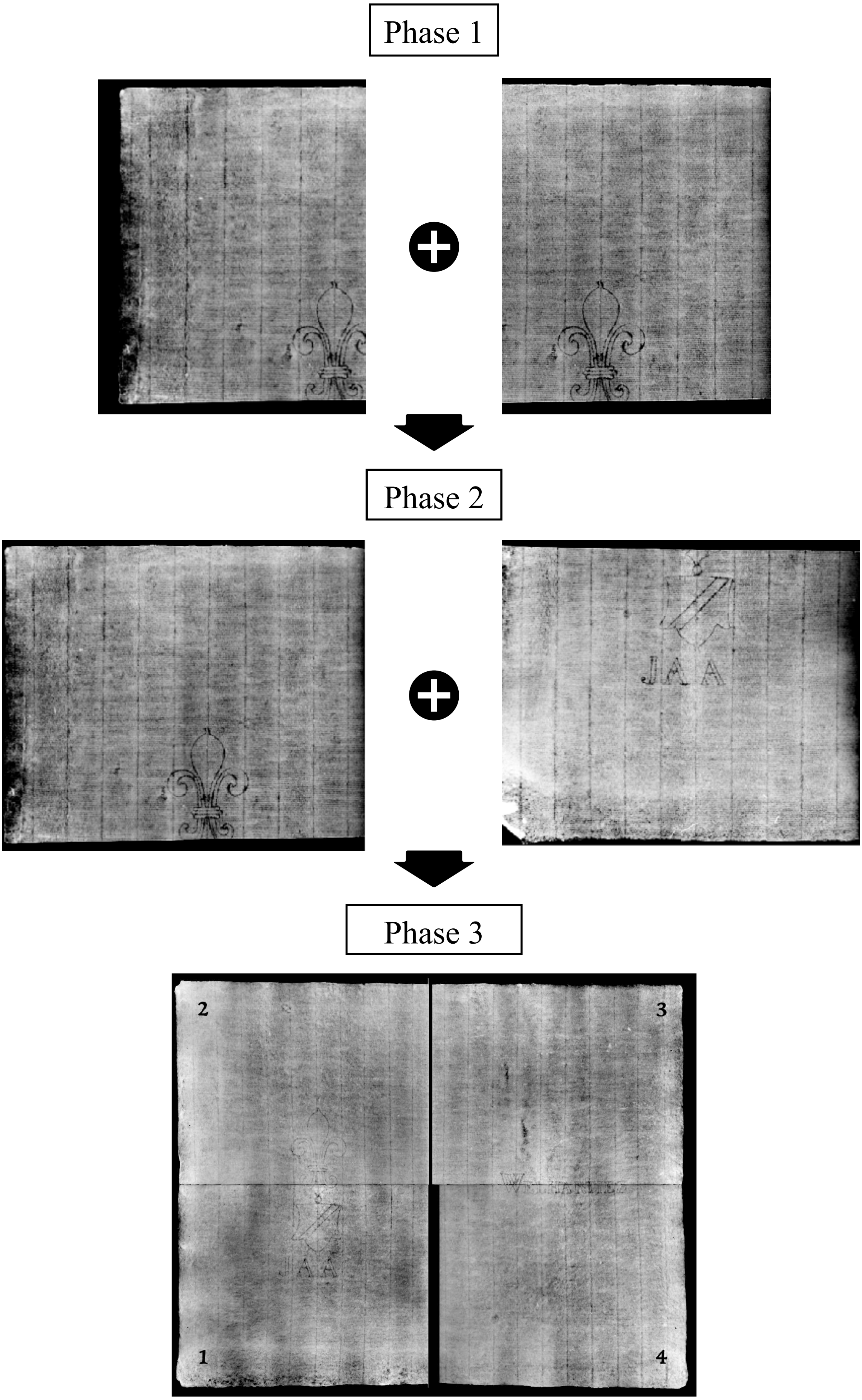

Fig. 11 - The steps necessary to reconstruct the original paper sheet
Source: MHc-12 - D 982 “Entwürfe für eine Oper”

sheet. In fact, the severing of the single quarto pages might have removed a considerable portion of the sheet. This may cause a not perfect matching between the two parts. Furthermore, as seen in Phase 3 of Fig. 11, it is not possible to fit all four parts of the original sheet: this is because of the loss of information in the binding during the digitisation phase and thermographic imaging, which does not allow perfect imaging of the entire sheet. However, the most important section of the sheet to reconstruct, the watermark, is successfully put together.

The final stage of the project, still being developed, is the signal processing and image matching of watermark images. In fact, once all the images of each sheet are reconstructed, an algorithm will be used to group these reproductions and compare them to find twin or identical watermarks[26]. For this step, signal processing methods are developed to calculate the difference between two patterns derived from the watermark images. Although not yet implemented, the process will follow these steps: images are preprocessed to obtain a clear representation of the watermark. Specific points, called characteristic points-of-interest, are extracted from the greyscale thermograms, an idea inspired by fingerprint recognition[27]. Each watermark will then be represented by a unique dot pattern, more readily processed mathematically than a simple image. In order to understand effectively the difference between two dot patterns, the "Earth Mover's Distance" will be calculated: this consists in evaluating the amount of translation movement needed for one pattern to coincide with the other. The quantification helps to identify watermarks which are almost identical (small difference values) from the ones differing considerably (higher difference values) and to cluster them together. This method will also be used to compare the differences between thermograms and tracings, with the analysis of potential errors in tracing recordings.

[26] Gulewycz P. et alia, op. cit, pp. 82-83

[27] Peralta, D. et alia, "A survey on fingerprint minutiae-based local matching for verification and identification. Taxonomy and experimental evaluation", *Information Sciences*, No. 315, 2015, pp. 67-87

3.4 - Limitations and further developments

Apart from the various advantages provided by the selected methods, as previously in earlier chapters, such as the quickness and consistency of thermographic images, several limits and potential improvements should be highlighted.

First, even though thermography resulted in being a safe and harmless method for the type of manuscripts issued in this project, the heat generated by the copper plate could be harmful for other types of more fragile sources, or inefficient in showing a clear image of the internal paper structure. For example, some medieval manuscripts are written using specific types of ink sensitive to thermal energy, and thus visible on the final thermograms. Furthermore, high room temperatures can affect the resulting images considerably, to the point that the heat difference between the copper plate and the surrounding environment is minimal. The thermographic system can then be used only under specific conditions.

Any damage to paper or its structure is visible via thermographic images. In the cases in which these superficial scratches overlay the watermark, the resulting watermark outline will be of lower quality or even absent. This is a limitation of the thermographic method as well as numerous other reproduction techniques. Infrared cameras, moreover, lack high resolution, which results in images of lesser quality compared to photographs.

Additional issues affecting the resulting reproductions can occur. Watermarks located near the binding (approx. under 5mm from it) are quite difficult to capture. The binding is indeed the area of the manuscript more exposed to heat from the copper plate and, as a result, dark in the final image. Watermarks positioned in this area are therefore more complicated to reproduce, and a considerable amount of information about the paper and its structure is lost. Meinlschmidt, who has used a complementary thermographic method in his research, proposes a technique to improve watermark image quality when located near the binding. This is achieved by optimising the image in the post-processing phase. The results are shown in Fig. 12.

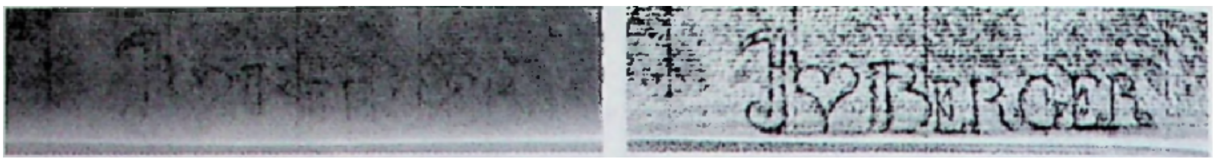

Fig. 12 - Unedited raw file (left) and optimized image of a watermark in in the binding (right). Source: D-B Mus.ms.autogr. Cherubini, L. 149, p. 18.

As already described, the thermographic camera system used in the DRACMarkS project was not able to capture the entire issued leaf in one shot, caused by the impossibility of regulating the camera angle. The subsequent merging of images in the post-production process may lead to some discrepancies. Even if automatised, the system of image merging still needs minimum control by an operator and, in cases of incorrect stitching, manual intervention. This protracts the time needed to obtain the final images useful for watermark comparison.
For a thermographic system similar to the one used in this project, costs are quite prohibitive. Only large institutions, in this case the Austrian Academy of Sciences, can actually afford such equipment for their research. Furthermore, to be more efficient, the digitisation workflow requires two operators to work simultaneously. In German-speaking countries, there are only six thermographic systems for the registration of watermarks. An idea to make the acquisition of this equipment more sustainable is to rent out the thermographic system to other research teams interested in watermark imaging. The advantage of it being a portable system makes it suitable for work in remote circumstances, such as old archives and libraries.

The various further developments offered by the here described methodologies of inspection are related both to the current thermographic system and to the future work that could be done using the resulting watermark reproductions and matching.
Since the thermographic system here presented is an innovative method for the reproduction of watermarks, it gives space for future improvements. First off, the limitations on the camera angle might be solved to permit the page imaging in a single shot, limiting the subsequent step of picture merging. In general, technological innovation of the thermographic camera, with the increase of its imaging quality, leaves room for new research on the application of this type of system to the study of watermarks and paper and, more generally, to the field of cultural heritage.
A huge achievement of this project is also the creation of the MEI extension for the registration of watermarks and paper structure information. The results are of great interest to musicological studies since the standardisation of such a format might help other research teams in the future. The idea is to check and implement, together with the MEI community, the model file created for the DRACMarkS, in order to generate a dedicated MEI extension for encoding watermark information.

The final images of the complete watermarks, the central achievement of this project, are a useful tool for musicological, bibliographical and historical research. In fact, once the matching system promoted by the DRACMarkS team is implemented, it could be used to find matching paper structures and twin moulds. This type of information, as vastly explained in this dissertation, can be used to collocate undated Schubert's manuscripts in the timeline of his works. Moreover, research results can be further investigated in order to look for paper mills from which the paper of the manuscript might have been produced. As mentioned by Robert Winter in his article "Paper Studies and the Future of Schubert Research", Schubert was a "creature of habit"[28], and around 90 percent of his autographs were written on fewer than 20 paper types, restricted to only a small number of paper mills. The relatively small number of watermark types inside Schubert's music manuscripts facilitates the research on the origin of this paper, limiting the geographical area of provenance to Bohemia, Northern Italy and the Netherlands. The possibility of actually recognising the paper mill of origin would help to trace the paper trade of the first 19th century, revealing different details about the changes occurring in the economic and political scene after Napoleon's fall.

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28 Winter R., op.cit, p. 214

CONCLUSIONS

This dissertation has aimed to explore the study of paper and watermarks and their application as bibliographical tools, concentrating on the most recent developments in filigranology and its encounter with digital humanities. The significant aid that paper studies can bring to other subjects like history or bibliography is by now ascertained and confirmed through very different research projects in numerous disciplines. In the past century, the delineation of a method for filigranological analysis has led to a definitive appreciation of this subject as a concrete and objective support for the dating of hand-made paper manuscripts and printed sources. The further increase in trustworthiness of these techniques was reached also thanks to the most recent innovations of digital technologies, which have led to significant improvements to different aspects of the subject.

The best practices of digital methods for filigranology and their application have been concretised through the analysis of the DRACMarkS project. This recent and still developing case study has demonstrated to be in line with the latest achievements in the field by using cutting-edge methodologies for watermark research, without underestimating the precision required for a correct filigranological study. The team's conscious assessment of the available techniques, considering both their positive and negative aspects, has led to a concrete choice of methods and determination of the entire workflow, from reproduction to comparison of watermarks. The idea of substituting and implementing the previously fulfilled tracings should be the starting point of numerous other projects requiring modernisation. Choosing thermography for the imaging of watermarks, as well as the coherence in their description and archiving using the XML file following MEI standards are other strengths of DRACMarkS. These points are, as already explained, crucial for further consistent analysis and comparison of data, which will be achieved in the latest step of the project.

Speaking more in general about the digital approach to filigranology, three aspects have been at the centre of this thesis analysis. First, the reproduction techniques for watermarks are developing at a high pace, principally moving towards non-contact, fast and objective imaging methods. There are numerous strong points and several weaknesses to these techniques. As highlighted in Chapter 2, the methodologies are different and not unified among scholars and research projects, which are still experimenting to find the best digital approach to the reproduction of watermarks. The absence of a commonly shared method, with numerous projects still working with obsolete technologies, leads to discordance of information. After having analysed the various techniques available and directly tested the use of an infrared system at the DRACMarkS project, it is the author's opinion that thermography and back-lit photography are the best methods in circulation for watermark reproduction. Both proved to be efficient in terms of the time needed for the actual visualisation of the final image and the quality of resulting reproductions. On one hand, thermography has the advantage of being the fastest and simplest technique, but still too expensive for small institutions. On the other hand, a back-lit photographic system is more affordable, even though it needs an intermediate step for the actual visualisation of final reproduction, that is an algorithm for image subtraction. The latest multispectral systems used for paper study (e.g. Book2Net X71 Multispectral system[1]) are capable of automatically subtracting the front and back-lit image of paper at issue, and thus returning the final reproduction of the watermark in one simple step. These two imaging methods are equally valid solutions reaching satisfactory results. The homogenisation of reproduction technologies to one of these two methods would lead to higher-resolution images exploitable for further quality research.

Secondly, online collections, an extremely useful tool for filigranological research, are growing in number and are attempting to establish a common method for the registration of watermark information. However, the databases available today have not reached yet the highest possible development, leaving room for the implementation of more effective systems, complete with all the useful data needed for an objective and valid research based on watermark studies. The two major projects in the field, the Bernstein Portal and the WZIS database, are moving in the right direction, trying to aggregate more institutions and collections in a single website capable of offering complete and qualitative information. It is still ambiguous, however, what is the common standard preferred for the description of watermarks in these databases. Even though IPH has declared its own set of rules and guidelines for the complete analysis of hand-made paper sources, it is still not the one preferred in the field. On the contrary, the vast majority of the new online collections rising in recent years are opting for the standard created and fostered by the Bernstein project. This is leading towards a homogenisation of the watermark nomenclature. However, it still seems that these databases are unable to speak to each other because of their incompatible data formatting. A platform like Bernstein's "The Memory of Paper" can be the solution for a

[1] book2net.net/multispectral, Book2Net, *Multispectral Imaging System*. Last visited 12/09/2023

shared space in which watermark data are standardised and published. With the support of other important projects like WZIS, which is responsible for aggregating information in a single database and then sharing it on the Bernstein portal, the system of watermark description standardisation could reach a higher level of accuracy.

Finally, the application of pattern recognition and artificial intelligence has recently opened up new perspectives for the comparison and study of similar and identical paper structures and watermarks. The research into these continuously developing methods is the final frontier of filigranology, with numerous projects which are still today trying to develop a quality method for watermark comparison and matching.

To be as effective as possible, filigranological research asks for a large amount of quality watermark reproductions and information. Nowadays, the best and most effective way to achieve this objective is to use digital methods throughout the entire process. These help also to standardise the used techniques and to objectively gather, publish and compare filigranological data. The homogenisation of methodologies and quality standards are crucial aspects for the future of research in the field. DRACMarkS has proven to be an excellent example to be taken into consideration for the development of a fulfilling digitisation project, able to produce high-quality, coherent and comparable watermark images and data.

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APPENDIX

APPENDIX 1 - IPH CLASSES

The following list is the official group of main watermark classes defined by the IPH:

A. Human figures; men; parts of the human body
B. Women
C. Mammals
D. Birds
E. Fish, reptiles, insects, molluscs
F. Mythical figures
G. Plants (general); flowers; grass
H. Trees; shrubs; creepers
J. Sky, earth, water
K. Buildings, parts of buildings
L. Transport, vehicles
M. Defence and arms
N. Tools, equipment, clothing
O. Musical instruments
P. Containers
Q. Miscellaneous objects
R. Insignia of rank, sceptre, mace, jewellery
S. Religious or magic symbols and signs
T. Heraldry, coats of arms, mason's marks, trademarks
U. Geometric figures
V. Numbers, numerals
W. Individual letters
X. Monograms, abbreviations with letters
Y. Names (in full)
Z. Unclassifiable watermarks

Appendix 2 - List of figures

- Fig. 1 - Elias Porcelius, “Das wohlausgesonnene Pappiermachen”, in Curioser Spiegel, in welchem der allgemeine Lauff des ganzen menschlichen Lebens... vorgestellt wird, Nürnberg, verlegt bei Johann Endter, 1689;
- Fig. 2 - La Rue J., “Watermarks and Musicology”, *The Journal of Musicology*, Vol. 18, N. 2, 2001, p. 325;
- Fig. 3 - Screenshot from the Bernstein Portal, www.memoryofpaper.eu
- Fig. 4 - Screenshot from the Bernstein Portal, www.memoryofpaper.eu
- Fig. 5 - Screenshot from the Wasserzeichen-Informationssystem webpage, Reference number DE0960-Georg1M_1, www.wasserzeichen-online.de/wzis
- Fig. 6 - Courtesy of DRACMarkS project, Austrian Academy of Sciences
- Fig. 7 - Own production
- Fig. 8 - Tyson A., The Problem of Beethoven's "First" "Leonore" Overture, “Journal of the American Musicological Society”, Vol. 28, N. 2, 1975, p. 333
- Fig. 9 - Own production
- Fig. 10 - Courtesy of DRACMarkS project, Austrian Academy of Sciences
- Fig. 11 - Courtesy of DRACMarkS project, Austrian Academy of Sciences
- Fig. 12 - Meinlschmidt P., Immel H., “Digitale Dokumentation von Wasserzeichen mittels Thermographie”, in Eckhardt W. et alia (hrsg.), Wasserzeichen, Schreiber, Provenienzen: neue Methoden der Erforschung und Erschliessung von Kulturgut im digitalen Zeitalter: zwischen wissenschaftlicher Spezialdisziplin und catalog enrichment, Vittorio Klostermann, Frankfurt am Main, 2016, p. 212

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