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Study of an "Artefact" of the Castilla Canal: Reconstruction of the Missing Machinery †

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Abstract: This work aims to apply a systematic methodology to the analysis and graphical recovery of the "artefact" of the first lock of the Canal de Castilla ("the forge of Alar del Rey") located in the Canal de Castilla as it passes through the province of Palencia (Spain). The canal, a great engineering work that began in the 18th century, was declared an asset of cultural interest (BIC, for its acronym in Spanish) in 1991 and was included in the National Plan for Industrial Heritage. To analyze and to obtain graphic reconstruction proposals, six main activities were developed, following three phases (study of primary and complementary technological and historical sources, fieldwork, and digital reconstruction). The reconstruction proposals were evaluated using three criteria: artefact data, the number of similar artefacts, and the performance. The weights of these three criteria were obtained using the Best-Worst Method (BWM), and the reconstruction proposals were classified using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) under uncertain conditions. AutoCAD was used to obtain detailed artefact geometric documentation (plans and detail drawings of each element). The work carried out on the artefact has allowed the reconstruction of the missing machinery and its factory, establishing a proposal consistent with the technological solutions of the end of the eighteenth century as well as with the ironworks studied and with the documentary sources consulted, recovering the memory of an artefact that is about to be lost.

Keywords: industrial and technological history; machinery of forges; Castilla Canal; study methodology

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1. Introduction

There is a general consensus that testimonies related to the culture of work are part of cultural heritage [1,2], its role in sustainable development [1,3–6], and its interpretation as a tourist resource [7] or a cultural resource [8]. In all these contexts, machinery and engineering play an important role [9]. However, administrations have serious difficulties declaring industrial goods as assets of cultural interest (BICs, for the acronym in Spanish) [10]. A first classification of industrial heritage [11] is that of tangible heritage and intangible heritage, which together constitute so-called cultural assets. The first group includes material goods of industrial and non-artisan origin, such as material objects with cultural value either due to their historical, technological–scientific, or industrial design significance, which, in turn, can be divided into movable goods such as objects, artefacts, electrical appliances, machines, and technological devices and real estate, in the architectural sense [12]. In particular, movable goods can be classified again into capital movable goods and durable consumer goods. The theory of industrial heritage should cover both the former, originated by engineering, and the latter properly framed in industrial design; this is not always taken into account. On the other hand, there is real estate motivated by architecture. Hence, there is a need to relate the history of architecture with the history of the techniques and technology of the engineered devices, machines, and processes and with the history of the techniques and technology relative to the products. For its part, in tangible or intangible industrial heritage, also known as living heritage, includes, among other concepts, the ways of life within productive areas, customs, and industrial traditions, and the know-how or secrets of the productive processes carried out by the workers themselves [13].

Industrial heritage has its own interdisciplinary methodology called industrial archaeology. This term was used in 1955 by Michael Rix [14] and defined in 1963 by Hudson [15]. In this way, archaeology, its methods and techniques were placed at the service of the study of the industrial past, allowing for its reconstruction based on the remains and data collected [16]. To analyze the role of movable industrial heritage; understand the operating mode of the machines, the working conditions of the industrial process, and the design of the machines; and to propose criteria for possible new interventions, a systematic methodology is necessary. Any intervention project on certain elements of industrial heritage requires a methodology that considers their state over time and their value for new use [17]. Their state and use may have changed over time, but all previous uses should be investigated and evaluated [18–20]. In this sense, current studies show the value and relationship of the machines [9,21], their industrial processes [20], and the factory itself [21–23].

The Canal de Castilla is included in the National Plan of Industrial Heritage as one of the industrial assets that should receive the maximum protection granted by the legislation on historical heritage (Spain, Decree 154/1991). It has also been included in the catalogue of the 100 elements of industrial heritage in Spain drawn up by the Spanish section of The International Committee for the Conservation of the Industrial Heritage (TICCIH). This historic site includes both the hydraulic works (docks, careening docks, locks, retentions, sections between sets, bridges, aqueducts, culverts and beacons) and the buildings (lock keepers' houses, factories, warehouses, warehouses and workshops). All these installations have an unquestionable historical, cultural, and, in some cases, monumental value, with varying degrees of protection.

Among all of them, this work focuses on those which, during the 19th century, received the peculiar name of "artefacts" in the Canal de Castilla. In the context of the Canal de Castilla, the term "artefact" should be understood not only as the machines, apparatus, and "mechanisms destined to the obtaining, transformation and conduction of substances" or to "the production of energy" (National Plan of Industrial Heritage; 2016 update), but also as the whole building with machines moved by hydraulic energy for different uses. While until the first half of the 18th century the word "artefact" (arte factum, "made with art") simply denoted (as is the case nowadays) a machine, a piece of apparatus, or a device, from the second half of the 18th century onwards, the term "artefact" came to refer to both the machines and the building as a container. Indeed, in the period of the greatest industrial development of the Canal de Castilla (end of the 18th and 19th centuries), the documents consulted refer to the "artefact" as an inseparable whole and, in short, they speak of an industrial establishment, a manufacturer or a factory in which there are machines or apparatus (built with a certain technique for a certain purpose). In fact, faced with the "confusion and lack of accuracy" of the definition given by dictionaries (in which only etymological reasons are taken into account), in 1852, Lorenzo Arrazola [24], a 19th century jurist and politician, saw the need to give a correct definition, from a "scientific and practical, legal and administrative" point of view. According to her, the term "artefact" is understood to mean "not only the machine, but everything that serves for its movement and use", including "the building arranged for its installation" and the waterfall, an interpretation fully in line with the usual use of the term in the 19th century. This evolution towards the identification between content (machines) and container (factory) in the 19th century is not exclusive to the word artefact. As is well known, it also occurred in words referring to specific establishments, such as molino (milling machine and building containing a mill), batán (fulling machine and building with fulling mills), and martinete (hammering machine and building containing it). An artefact is therefore any building with its water-powered machinery built along the canal and intended exclusively for industrial use. Unfortunately, these artefacts have been systematically forgotten, and in many cases, they have either been definitively lost or have deteriorated so rapidly that they are likely to disappear. In the case of the Canal de Castilla, these artefacts have been systematically forgotten.

The objective of this work is the analysis and graphical recovery of the "artefacts" of the forge of the first lock of the Canal de Castilla ("the forge of Alar del Rey"). In order to achieve this objective, a systematic methodology was applied. From its preliminary analysis, it was possible to select the artefact object of this study (the artefact of the first lock) mainly based on criteria of temporality (it is one of the first industries of the canal), singularity (due to its rarity or exceptionality in the geographical environment in which it is located), and existence of data (none of the artefacts have survived and for none of them does the preliminary analysis show more than a minimal amount of graphic data for their reconstruction). To analyze, graphically recover this installation, and recreate its appearance, machinery, and original functioning, engineering graphics as well as technological and historical studies are fundamental tools. Using engineering graphics is also a fundamental part of the computer-aided design process [25]. Tools such as AutoCAD© allow to obtain its detailed geometric documentation (exploded view, assembly plan, and detailed drawings of each element) [26]. This work shows a technological and historical study together with fieldwork to achieve a graphical reconstruction of an artefact that is about of disappear.

The rest of the article is structured as follows: Section 2 presents the case study and our research procedure, Section 3 describes and discusses the results obtained, and the conclusions reached by this work are summarized in Section 4.

2. Materials and Methods

Next to the first lock of the Canal de Castilla, a metallurgical business was located: a forge. It is located approximately 2.5 km from Alar del Rey in the town of Barrio de San Vicente (Palencia). After being built and functioning as such for a few years, the forge was abandoned and ended up housing a hydroelectric power plant once the 20th century began. It is in ruins and without machinery. As a starting hypothesis, there is a specific initial industrial process for this artefact; this industrial process was described by Juan de Homar in his memoirs (Homar, 1800) [27]. Homar refers to this artefact as a "Mallet for the construction of collars, tongs, weavers, chevrons, jacks, carriage fittings, nails of all kinds and many other tools...". In 1800, this metallurgical establishment was being completed, mainly oriented to the manufacture of tools for the works of the canal itself and for different agricultural activities. The engineer director of the canal confirmed the use of this establishment in a graphical document in 1806 (Figure 1). The intervention of military engineers was decisive in the public works of the 18th century [28]. Their knowledge in the field of hydraulic works was high, and the Canal de Castilla was a model of experimentation. Everything indicates that Juan de Homar, Engineer Director of the Royal Canals, was a true promoter of its industrial use at the proposal of Francisco Sabatini, Director of the Corps of Engineers [29,30].

The main accessible dimensions of the artefact were taken with a tape measure and then checked against those provided by various historical documents. For the more inaccessible dimensions or those of missing elements, it was necessary to use and contrast the dimensions provided by different documentary sources, such as valuations and inventories and 20th century transformation projects. The international metric system was not imposed in Spain until 1849, and until well into the 20th century, the measurements of the old system continued to be used. Most of the historical documents show dimensions in feet for the artefacts of the canal. The foot as a unit of length was used in most Spanish regions, although not all of them had the same measurement. In Castilla, the Castilian foot was used, also known as the Burgos foot. This unit, according to the tables of reciprocal correspondence (royal order of 9 December 1852), was equivalent to 0.835905 m. The Castilian rod is equal to 3 feet. In this work, the following relation was considered for all calculations: 1 Castilian foot (or Burgos foot) = 1/3 Castilian rod = 0.278635 m. Some 20th century projects, such as that for the transformation of this artefact into a hydroelectric power station (Fungairiño, 1922), show (already in meters) precise and rigorous dimensions [30]. These measurements were also used in this work (Figure 2).

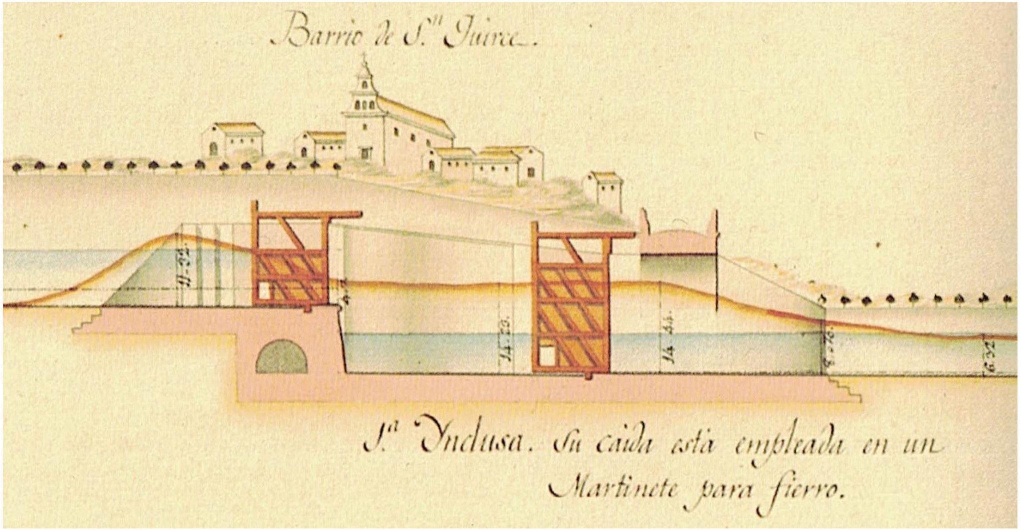


Figure 1. Graphical representation of First lock of the Canal de Castilla. Source: Juan de Homar, Archive of the Royal Palace of Madrid (1806).

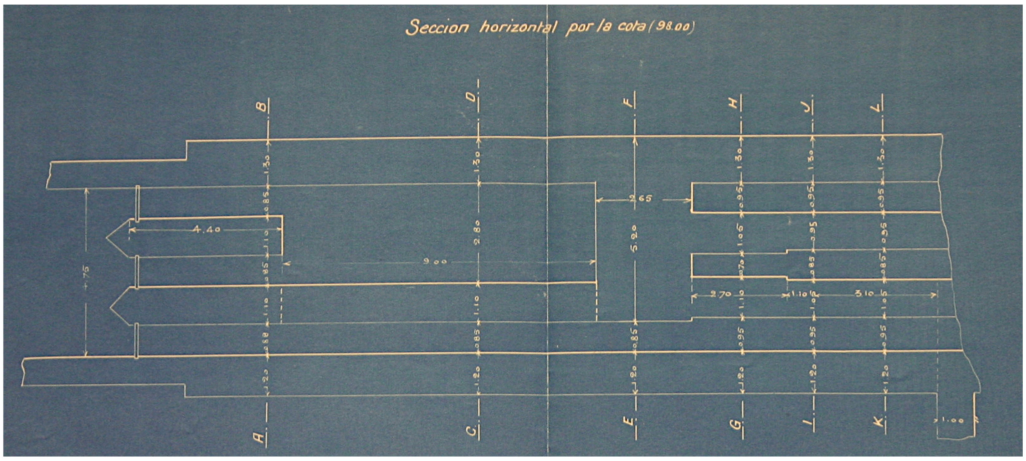


Figure 2. Dimensional data of hydroelectric power station project. Source: General Archive of the Duero Hydrographic Confederation, FACC, PCC, C-2177, PYTO-2601.

The graphic reconstruction of the mallet with its machinery, as a step of synthesis of all the data, was carried out with AutoCAD© using the dimensional precision provided by all the available data. The software allows us to draw up complete plans. The plans show the location of the different rooms and original machines, and they include the construction details of the machines for their correct interpretation. These tasks are essential for knowing and understanding the operation of the machines.

Geijo et al. [2] propose a general methodology for the enhancement of the industrial heritage of Castilla y León based on five phases. A revision of this methodology applied to the study of a specific artefact can be summarized in four phases (selection, study of primary and complementary sources, fieldwork, and digital reconstruction). Table 1 shows the main steps associated with each phase and their specific objectives. The phases and steps in Table 1 are in agreement with industrial heritage studies [16,31].

Table 1. General methodology. Source: own elaboration.

Phase	Steps	Specific Objectives
1: Selection	Selection criteria of case studies/technological analysis of the different elements selected. Decision basis: previous stages. Analysis of a significant sample.	O1: Determine case study: Know, identify, and value artefact.
2: Study of primary and complementary sources	Document review: bibliographic sources. Review of graphic sources (plans and drawings).	O2: Analyze original use and the artefact's machinery. O3: Compare results with similar artefacts.
	Indivisible element: movable industrial property/immovable industrial heritage. Historical/economical/geographical/social and cultural aspects. Typology of factories.Production processes. Materials and technologies. Correct industrial furnishings extracted from the original context.	
3: Fieldwork	Fieldwork: in situ recognition of the selected sample: work sheet, geographic referencing. State of conservation: movable and immovable property. Comparison of reality with graphic documents: if both exist: error checking in the graphic representation. Review of factory execution projects or remodeling projects, if applicable.	O4: Verify data and study the real situation of artefact.
4: Digital Reconstruction	Analysis of the specific documentary sources of each case. Graphic reconstruction: if only documentary evidence exists. Formulation of graphic reconstruction hypotheses: in the case of the physical inefficiency of the industrial object and of the graphic and/or written documentation that describes it.	O5: Reconstruct the artefact graphically. O6: Contextualize the artefact and its machines.

Following this, Geijo et al.'s methodological approach, and a focus on the analysis and recovery for the reconstruction of the building of the first lock with original machinery of the forge of Alar del Rey, six main activities were considered (Figure 3). These activities follow the systematic design approach of Pahl and Beitz described by Fiorineschi et al. [32]. Although the applicability of the approach described by Fiorineschi et al. has more impact on the design of a physical device, the six proposed activities of this study could be a group of tasks for developing a conceptual, embodiment, and detailed design of the artefact in a heritage study context. All these activities are connected to each other and are related to the proposed objectives, as shown in Figure 1. Fieldwork and the creation of graphic models and virtual simulations greatly help us understand and value movable assets in the science of heritage [33,34].

In this type of study, it is common that some of the information has been lost. The analysis of the current situation of the artefact and its historical and technological documentation together with the study of the set of documentary sources and artefacts of its geographical environment and time requires an evaluation methodology that allows choosing the most appropriate reconstruction of the machinery and the building itself with the available information.

The working hypothesis is the reconstruction of the artefact taking into account three criteria: artefact data, number of similar artefacts, and performance. Artefact data refers to the adequacy of the proposed reconstruction with respect to the historical information, its physical state, and the available graphic and engineering data. The number of artefacts is the ratio between the number of artefacts found and the number of artefacts using the reconstruction proposal. Finally, performance considers the technical suitability of the proposal to its site.

In order to evaluate and select the best artefact reconstruction alternative that suits the available data, it is necessary to use a multi-criteria decision-making method (MCDM). A large number of MCDM methods have been developed [35] and their applications are widespread in fields such as business [36], land allocation [37], the transport sector [38], modal analysis of failures and effects [39], and heritage engineering [40]. In our case, to obtain the weights of the three criteria, we propose to use the Best-Worst Method (BWM) [41]. This method is quick and easy to use. In BWM, decision-makers start by determining the most important and the least important criteria. Then, the preference of the best criterion over all the other criteria and the preference of all the criteria over the worst criterion is determined using a Likert scale between 1 and 9. The criteria weights are calculated with the following optimization model of Equation (1), where w_j is the criterion weight j, a_{bj} is how much the decision maker prefers criterion j over the best criteria (w_B), and a_{jw} is how much the decision maker prefers criterion j over the worst criteria (w_w).

$$\begin{gathered} \underset{j}{\text{minmax}} \quad \left[\left(\left[\frac{w_B}{w_j} - a_{Bj}\right], \left[\frac{w_j}{w_W} - a_{jW}\right]\right)\right] \\ \text{s.t.} \\ \sum_j w_j = 1 \\ w_j \geq 0,\ all\ j \end{gathered} \tag{1}$$

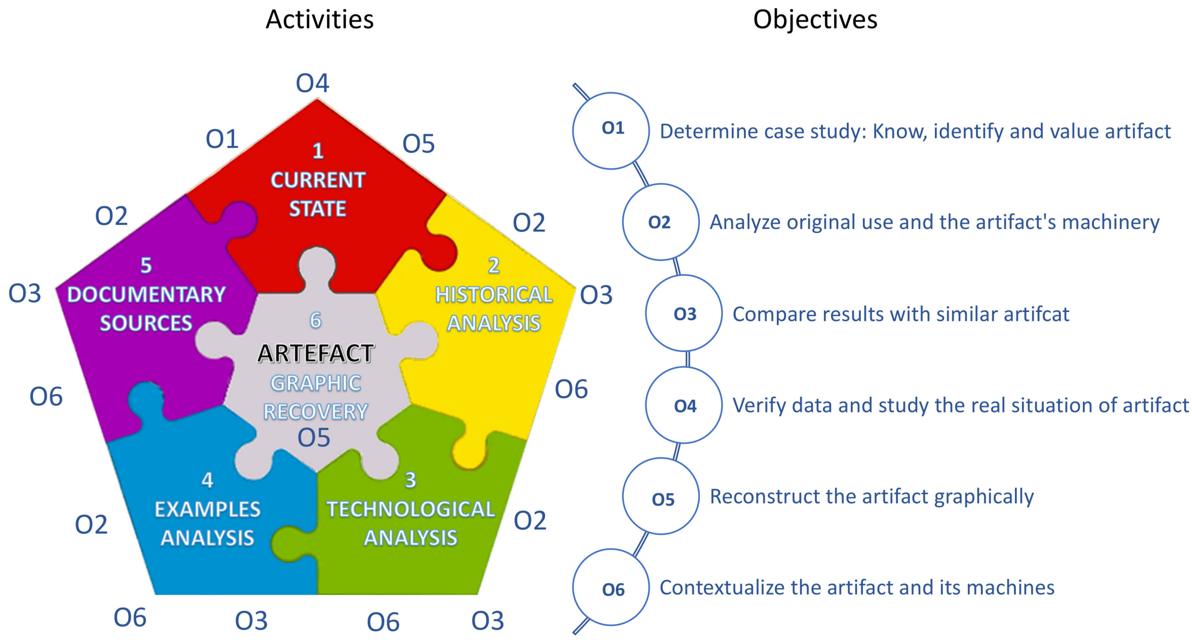


Figure 3. Main activities and objectives. Source: own elaboration.

To select the artefact reconstruction alternative that best suits the studied data, we propose to use the Technique for Order of Preference by Similarity to Ideal Solution under uncertain conditions (Fuzzy TOPSIS), following the approach of Chen et al. Fuzzy TOPSIS is a mathematical approach to select the optimal solution by simultaneously measuring the distances of each alternative to positive (most preferred alternative) and negative (worst alternative) ideal solutions [42]. The different alternatives are evaluated for each of the three proposed criteria using Table 2. The criteria values obtained by the BWM method are proposed to be used as weights.

Table 2. Criteria: type, assessment, and value.

Criteria	Type	Assessment	Value
Artefact data	Benefit	Quantitative	0 (no data)–5 (outright data)
Number of artefacts	Benefit	Ratio Quantitative	0 (no artefacts)–5 (all artefacts) (normalized)
Performance	Benefit	Quantitative	0 (worst suitability)–5 (optimal suitability)

The uncertainty in the evaluation process and the estimation of the weights obtained by the BWM method was incorporated by fuzzy logic [43], using positive triangular numbers (Table 3). Figure 4 summarizes the evaluation of the described artefact design proposal.

Table 3. Fuzzification of score of alternative i with respect to criterion j (S_{ij}) and weight of the criterion *j* (w_j).

	Value	Triangular Fuzzy Number
Alternative score	$S_{ij} = 0$	(0.0, 0.1, 0.25)
	$0 < S_{ij} \leqq 1$	(0.25, 0.5, 1.0)
	$1 < S_{ij} \leqq 2$	(1.0, 1.5, 2.0)
	$2 < S_{ij} \leqq 2.5$	(1.5, 2.0, 2.5)
	$2.5 < S_{ij} \leqq 3.0$	(2.0, 2.5, 3.0)
	$3.0 < Sij \leqq 4.0$	(3.0, 3.5, 4.0)
	$4.0 < S_{ij} \leqq 5.0$	(4.0, 4.5, 5.0)
Criteria weight	w_j	$(0.77 \times w_j, 0.93 \times w_j, w_j)$

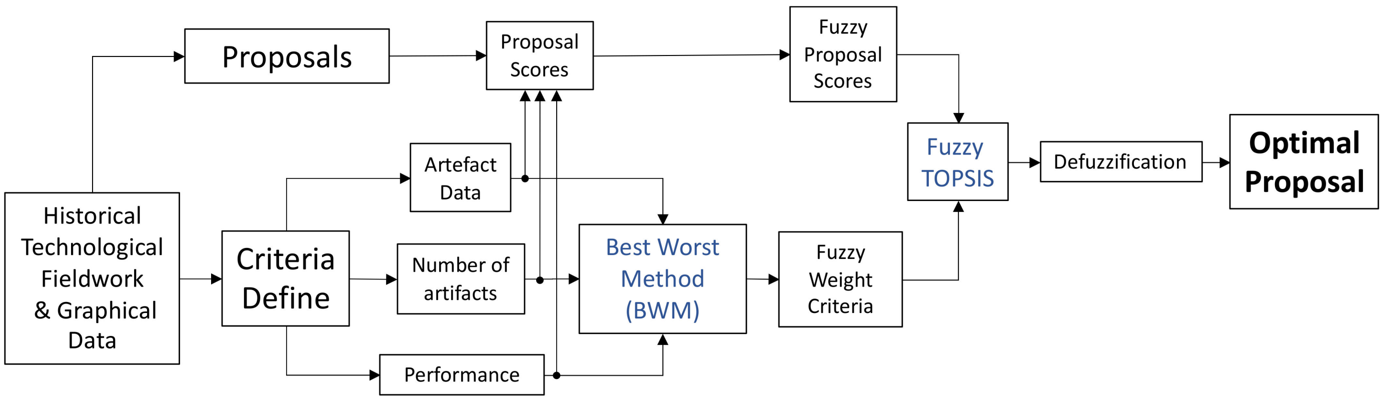


Figure 4. Overall proposal of artefact design evaluation.

3. Results and Discussion

This section presents and discusses the results obtained in the six activities carried out in this work, as the Material and Methods section describes.

3.1. Study of Primary and Complementary Sources and Field Work

3.1.1. Activity 1: Analysis of the Current State of the Artefact

The current state of the artefact was examined. Data and measurements were taken, and surveys of all the accessible elements of the forge were carried out. In addition, any other types of indirect data were considered, such as plans, drawings, recent photographs (regional plan, books and publications, etc.), old photographs, and aerial views, that could confirm the data of the artefact under study (Figure 5).

Although in a dilapidated state, this was a larger project than in the rest of the areas in other locks and docks. The floor plan was noticeably square, organized around a courtyard with two floors above the diversion tank. The body of water, divided into several channels at the entrance to take advantage of a total slope of 3.02 m, was completely distorted in the interior after its transformation into a hydroelectric power station. Once its industrial use was complete, the degradation of the building accelerated (Figure 5) due to the neglect of its initial function. The Regional Plan of the Canal de Castilla [44] includes this building in the cataloguing and protection sheets (grade III) with the name "hydroelectric power station" and original use of "mill" without specifying a date of construction other than a long period of 1759–1804. Currently unused, the building retains some mechanism for regulating the water intake for the device, but none of the original machinery remain.

Figure 5. Orthophotos 1977, 2009, and 2021. Source: http://ftp.itacyl.es/cartografia/01_Ortofotografia/ (accessed on 2 February 2022).

3.1.2. Activity 2: Historical Analysis of the Metallurgical Production Process

The main problem encountered by ancient cultures was the high melting temperature of iron (1535 °C), which was unattainable without using furnaces fueled with powerful blowing machines. Primitive ironworks, located near ore deposits, with furnaces that did not exceed 600 °C and did not include intervention from any machinery allowed us to obtain iron objects without melting iron by means of two basic processes: smelting and forging [45]. The first great revolution in iron technology occurred in the Middle Ages with the use of hydraulic energy to operate, in a less laborious way, larger hammers and various blowing machines. In this way, it was also possible to obtain wrought iron at a lower cost and to produce pieces of greater size and more complicated geometry [46]. The "major" ironworks were differentiated from the "minor" ones, a distinction that was not based on the size or magnitude of the facilities but on a division of labor and distribution of roles [47]. This type of water-powered ironwork remained in use until the 19th century, when the use of the steam engine for all types of applications spread.

The most primitive blast furnaces were usually built not only near ore deposits but also on mountain tops exposed to the prevailing winds to provide fuel for combustion. Without the intervention of some mechanism, the furnaces in these primitive forges did not exceed 600 °C. However, it was possible to obtain iron objects without melting them using two basic empirical processes: hamming and forging. In the slagging process, the doughy mass was beaten by hand (with a hammer) to drive out the slag and stick the unmelted iron particles together after the ore was heated in the furnace. In this way, the casting was obtained, which was finally given the appropriate shape, depending on the intended use in the forge [45].

Smelting in low furnaces was greatly improved by the use of foot bellows operated by the forgers' feet or hands. Temperatures near 1300 °C were reached in this manner, allowing the hot billet or "agóa" to be produced. Later, the hot billet was hammered [48,49]. The use of hydraulic power to actuate bigger hammers and various blow molding machines in a less laborious manner was the first great revolution in iron technology in the Middle Ages. This technology also allowed for lower-cost wrought iron and the production of bigger parts with more complex geometries. In the 12th and 13th centuries, the use of water wheels to power iron hammers and move blow molding machines in the forge spread throughout Europe. In Spain, there were explicit references to forges with water hammers, or "martinets", at the beginning of the 14th century [46]. These water hammers quickly became widespread in northern Spain, where the climate and orography provided abundant wood for making charcoal and sufficient slopes so that the water from the rivers could move the machines.

3.1.3. Activity 3: Technological Analysis of the Machinery of Forges

The most important graphic descriptions come from classical authors such as Mariano Taccola (1433), Giorgio Martini (1484), Spechtschart vomn Reutlingen (1488), Vannoccio Biringuccio (1540), Ludwig Lässl (1556), Agostino Ramelli (1588), Georgius Agrícola (1556), Heinrich Schickhardt (1610), Leonardo Turriano (1622), Georg Andreas Böckler (1662), Christoph Sturm (1718), Villa-Real de Berriz (1736), and Suárez y Núñez (1784), among others.

Technical solutions derived from the great medieval invention of cams predominate in iron technology applications. The water wheel, used many centuries before for the grinding of grains, was newly applied in industries that required reciprocating movements. The mechanism used, the camshaft, allowed hammers, mallets, or rammers to regularly move to hit different materials. Additionally, the same technology was applied to rhythmically operate the bellows of the ironworks. The mechanism of the hydraulic ironworks was very simple and, precisely because of this, very effective. The hydraulic wheels, always vertical, transmitted the rotation directly to a shaft, and the cams embedded in it were responsible for rhythmically lifting the mallet and compressing the bellows or "barquines" (always in pairs to give continuity to the air flow) that stoked the furnace fire. Agricola [49] was the first to apply a simple lantern gear system to reduce the speed of the water wheel. The most convenient hydraulic motors according to Villa-Real [50] were vertical wheels with gravitational blades located below the "antepara" (elevated water tank) (Figure 6, left) and Vitruvian-type wheels when the height of the "antepara" did not allow water to fall on the wheel (Figure 6, right).

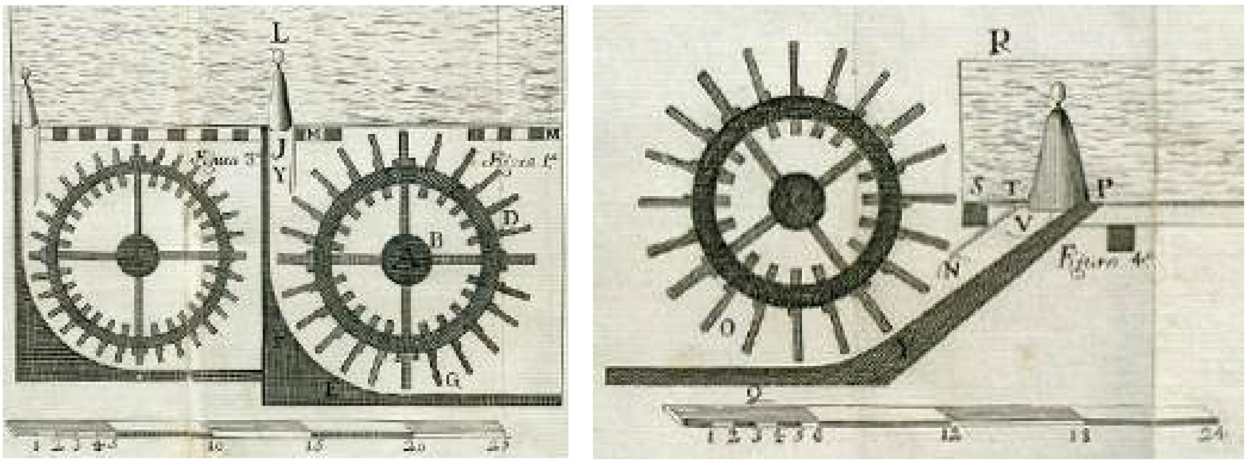


Figure 6. Gravitational and Vitruvian wheels according to Villa-Real [50].

Due to its influence on the training of 18th century engineers, the solutions and technical possibilities provided by Sturm [51] in his *Complete Mill Architecture* and by Belidor [52] in his *Hydraulic Architecture* are noteworthy. Diderot's [53] French *Encyclopaedia*, an emblematic work of the Enlightenment, gathers and disseminates knowledge about the mechanical arts applied to ironworking in different entries such as "forges" (forges, smithies), "soufflets" (bellows), "fourneaux" (furnaces), "martinet" (hammer), and "forge des ancres" (anchor forging). The assembly of a forge at the end of the 18th century did not incorporate great advances and continued to use technical solutions developed in previous centuries, including the lantern and crown gear system for the bellows wheel, as described and represented by Bertrand [54] (Figure 7).

It was possible to move the forging machinery with one or two water wheels (one for the mallet and the other for the large below). If the blowing system was independent of the machinery, manually operated bellows could be used, as well as water tubes (in uneven terrain that allowed for differences in the level of more than five meters). In cases where two wheels were present, Villa-Real distinguished between the mallet wheel and the

Barquines wheel, providing rules in his treatise to determine their different dimensions and number of blades depending on the height of the jump. These dimensions were determined by the various rhythms required for the movement of the mallet and bellows (Figure 8).

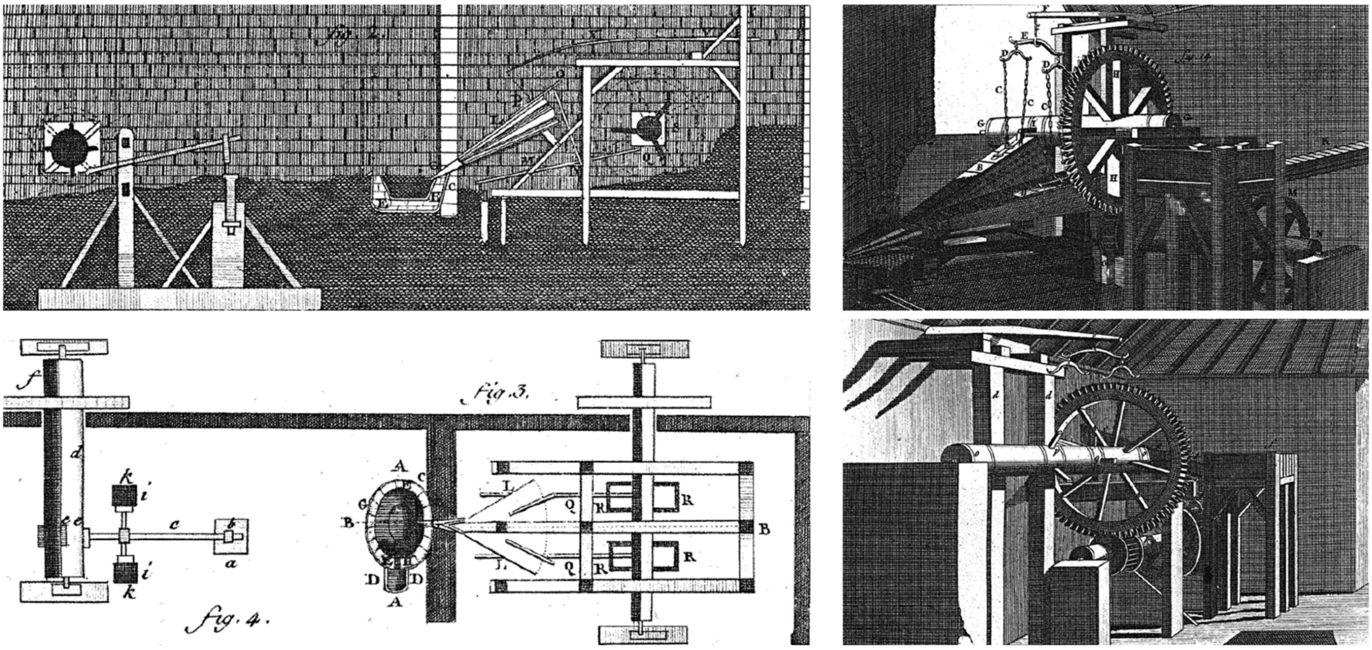


Figure 7. Ironworks and bellows drive. Source: Bertrand (1774) [54].

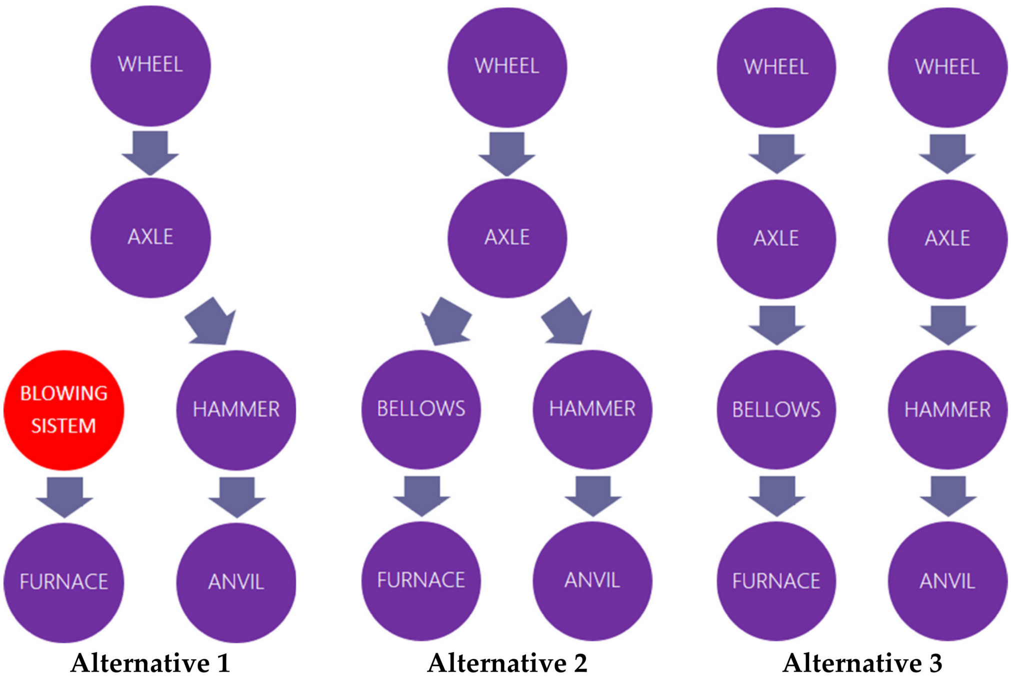


Figure 8. Diagrams of the operation of a hydraulic forge. Source: own elaboration.

3.1.4. Activity 4: Analysis of Examples of Ironworks and Forges

In small ironworks of Spain, such as Compludo (León), Navafría (Segovia), or Teixois (Asturias), with fires blown by tubes or "roncaderas", the hammer or tail-activated "machuco" was preferably used (based on the first-degree lever).

The elevation systems were the same in medium-sized ironworks examined in Spain, such as Mirandaola, Agorregi, Ybeltz, (Guipúzcoa), El Pobal (Vizcaya), Cades, La Iseca

(Cantabria), and Sargadelos (Lugo). Both Villa-Real [50] and Arroyo and Corbera [55] confirm that tail-actuated hammers were the most widespread in the foundries of northern Spain. The division of the workshop into two rooms (one for the harness and one for the bellows) was also observed, and two vertical drive wheels were used to drive the corresponding camshafts without intermediate gears. The wheels were located under the so-called "hydraulic tunnel" and their axles entered the forge workshop through holes drilled in the wall known as the "estolda" [50]. The layout of the auxiliary rooms is a little more erratic.

In all the examples studied, the main elements of the workshop (bellows, furnace, and hammer) were arranged in a straight line. The forge was always supported on a stone base or wall and attached to a wall that, according to Villa-Real [50], "divides the furnace from the bellows, which they call "bergamazo", and that "it must be at right angles to the wall of the "estolda" and that of the charcoal pits . . . ". This wall, called "bergamazo", divided the workshop into two interconnected sections and protected the bellows from the high temperatures reached in the furnace. The combustion was stoked thanks to the air received from the bellows through ducts called "nozzles". Due to their functional similarity, some anchor factories in Spain, such as that of the island of León (Cádiz) and that of Povedal in Marrón (Cantabria), as well as Reales Fábricas such as Fagollaga and Santa Bárbara (Guipúzcoa), Liérganes and La Cavada (Cantabria), and the Real Fábrica de Armas of Toledo were also analyzed. In these anchor factories there were usually complementary hammers to the main "office" of anchors and adjoining smaller forges, although without notable variation concerning the traditional installations: the hammer was driven by the tail using a hydraulic wheel whose direction of rotation was opposite to that of the bellows wheel (so that the cams could act correctly in both cases). In Gerona, the Real Fábrica de San Sebastián of Muga in 1771 used lantern gears in the blowing of the furnace, studied with precision by Belidor [52] and applied by Diderot [53] (Figure 9).

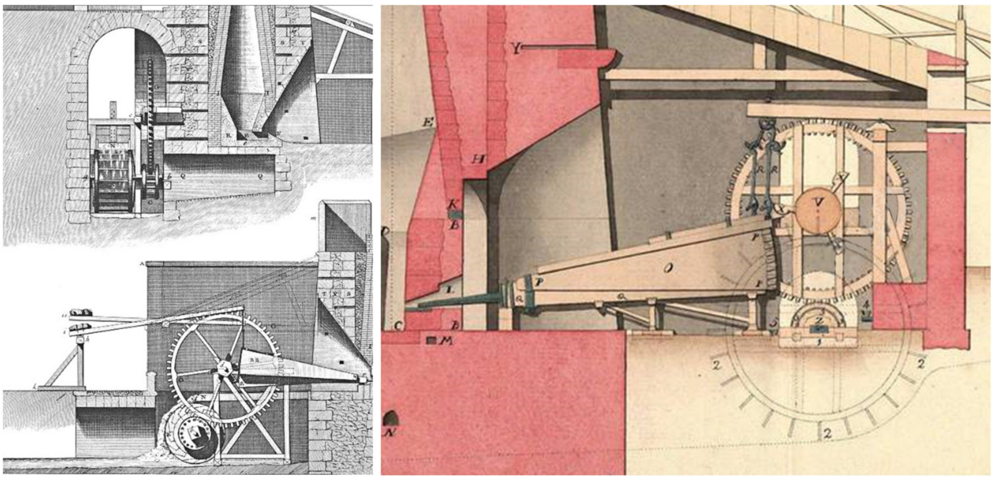


Figure 9. Gears and bellows according to Diderot (1756) [53] and Del Rey (1771) [56].

Depending on the size of the installation, there could be other rooms: warehouses for iron, tools, furnace fuel (straw, wood, or charcoal), and, in the larger forges, iron ore. In some of them, a small office or room was reserved so that the forgers could be away from the force of the fire as long as the smelting process allowed.

3.1.5. Activity 5: Detailed Analysis of the Sources

Most of the testimonies related to the canal are kept in the General Archive of the Duero Hydrographic Confederation (AGCHD, for its acronym in Spanish) of Valladolid.

By 1800, the iron hammer was about to be completed according to the Engineer Director of the canal [27]. Subsequent descriptions and appraisals confirm that in 1811, it ceased to function as such, most likely due to the Spanish war of independence (1808–1814).

The inventory of Rafo [57] confirms the existence of part of the machinery (a wheel with an axis of movement and some bellows) and the distribution and offices of this artefact: warehouses for the rough and refined iron, a haystack, a woodshed, a forge, and a raft for the movement of the machines on the ground floor and rooms for the workers on the second floor.

The plan of the forge from the beginning of the 20th century (attributable to Luís Alonso, overseer of the canal in approximately 1901) allows the general organization of the forge to be identified based on the dependencies referred to in the inventory of 1851 but does not reflect the positions of the machines. Although with striking errors, the plan suggests the important massive ashlar that closed the water tank, the position of the furnace, and the only useful channel at that time [58].

The hammer was renovated in 1922 according to the project of the civil engineer D. Eduardo Fungairiño Fernández, the head of the recently created Duero Hydrographic Confederation (1919). The project consisted, in essence, of incorporating an 80 HP horizontal Francis Mirapeix turbine in the so-called artefact chamber and an alternator to produce electrical energy that would be transported to the nearby town of Alar del Rey. Although this intervention irreversibly distorted "the strange network of intake and drainage channels that exists today and undoubtedly responded to the special needs of the industry to which the building was dedicated in another time . . . " [30], the project includes a precise survey of the current state on that date.

3.2. Activity 6: Synthesis and Graphic Recovery

In general, an element of industrial heritage contains graphic information and historical and technological data. As mentioned above, the graphic synthesis is one of the first steps to understand and enhance the value of a heritage element. When the data are not accessible, we can apply the concept of "exploratory drawing" [59] in reverse engineering the inaccessible plans. The study of the remains of the forge and the metallurgical processes, analysis of the technology used in similar establishments and existing examples, examination of the documentary sources, and all "exploratory drawing" tasks provided us with a graphic construction of the artefact (plans, elevations, sections, and details) and allowed the reconstruction of the forge with its machines, recreating its original appearance and functioning.

For the building, the original design of the forge is based on an almost square plan (34.5 $\times$ 29 m) with a central courtyard, to which the body of water is attached laterally (east side) next to the "stolda" wall. This idea of aggregation follows the traditional patterns studied but with an important difference: the body of water is not elevated but low and, in addition, configured with a network of channels that allows its integration in the building and the use of the upper floor (Figure 10). On the ground floor, there were also various storerooms, both for coarse iron (from the larger forges) and processed iron and, next to the furnace, for fuel (straw, wood, and coal) and for working tools. While the lower floor was entirely dedicated to the industrial process, the upper floor was used for other complementary functions. Here, there were offices and rooms for the workers in the factory with access from the main staircase. In the south-east corner was the lock-keeper's quarters with independent access from the side of the locks. Finally, the upper floor was completed by a storeroom and the lock-handling room (with another secondary access from the north facade) (Figure 11).

The water body was divided into several channels at the entrance with a total difference in height of 3.02 m. Its interior has not been preserved due to its transformation into a hydroelectric power station in 1922. However, the old graphical documentation has made it possible to understand the original water body of the pile driver (inlet channels and artefact or machine chamber), which had a special layout, as shown in the different sections of the graphic reconstruction developed in this work (Figure 12).

Concerning the machinery of the artefact, following Figure 6 and taking into account all the data, there could be three possible configurations to move the forging machinery.

These three proposals have been analyzed following the evaluation proposal in Section 2. Four decision makers developed the evaluation, and the results were consensus-based. The weight criteria were calculated using the BMW method. The best criterion was the artefact data, and the worst criterion was the number of similar artefacts. Pairwise comparisons between best criterion and worst criterion and the other criteria and criteria weight are shown on Table 4. The consistency ratio threshold is 0.2087 [41]. The consistency ratio (Ksi*) was 0.1286, less than the threshold, which implies that it is acceptable.

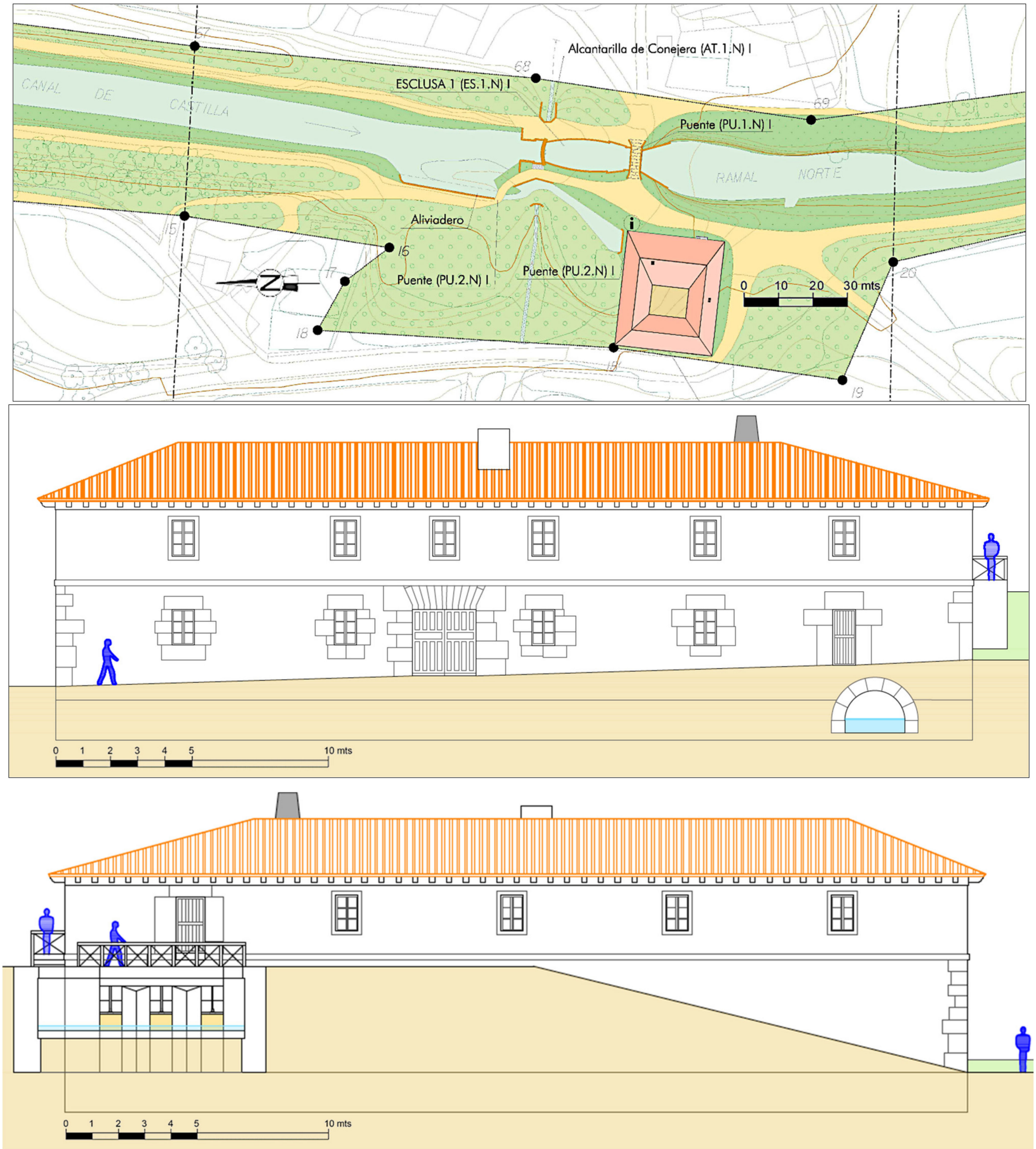


Figure 10. Location plan of the artefact and main facades (south and north). Source: own elaboration.

Figure 11. Ground and top floor of the artefact. Source: own elaboration.

Table 4. Weight criteria: BMW results.

Criteria	The Best to Others	Others to the Worst	Weight Criteria (Certainty Condition)	Weight Criteria (Uncertainty Condition)
Artefact Data	1	6	0.7286	(0.5610; 0.6776; 0.7286)
Number of Similar Artefacts	6	1	0.1000	(0.0770; 0.0930; 0.1000)
Performance	5	3	0.1714	(0.1320; 0.1595; 0.1714)

Table 5 shows alternative evaluation results. Alternative 3 has the highest score. The arrangement, dimensions, and characteristics of the machinery are in line with those of other traditional smithies. Unlike these examples, the existing difference in level in this lock (3.02 m) is clearly insufficient for using either blower tubes in the furnace or installing the classic "antepara" or elevated tank on the wheels. As this necessitates the use of Vitruvian wheels in the forge, the direction of rotation of the bellows wheel requires an inverter system to correctly operate the bellows.

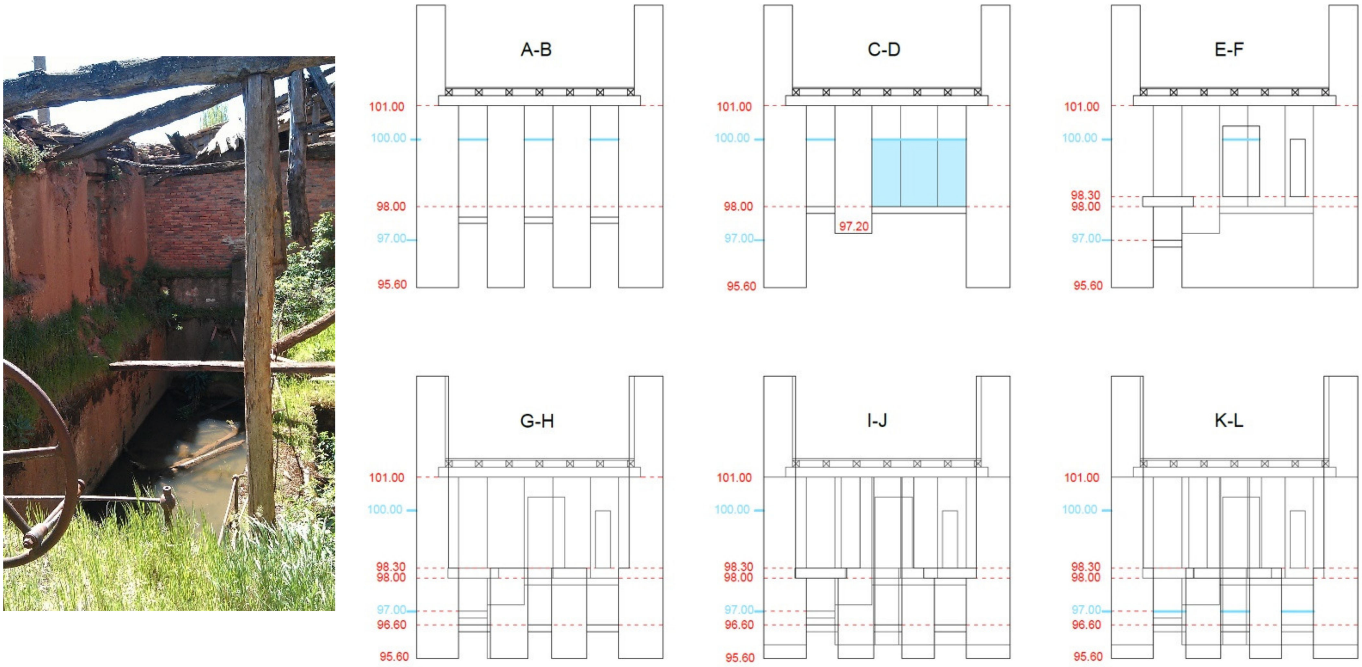
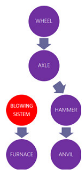
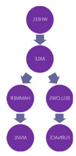
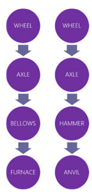


Figure 12. Current state of the water body and graphical reconstruction developed in this work. Source: own elaboration.

Table 5. Alternative evaluation: Fuzzy TOPSIS results.

Alternative	Fuzzy TOPSIS	Order Fuzzy TOPSIS
Alternative 1 	0.5214	3
Alternative 2 	0.8115	2
Alternative 3 	0.9374	1

The layout, dimensions, and original dimensions [30] of the water body (currently distorted and hidden) are fundamental elements for studying machines. The first element necessary in any water forge was the canal that supplied sufficient flow to work without problems throughout the year. Normally, it was necessary to build a dam or weir to transfer the waters of river to the channel that led the water to the water wheels, but here, in the Canal de Castilla, an intake in the upper part (upstream) of the lock was enough to lead it to the so-called body of water. This body of water consisted of three 0.85 m-wide inlet channels. The first, and closest to the "estolda" wall (inner channel), had a hydraulic jump of 1.95 m as soon as it entered under the building and continued independently as far as the outlet gully. The next two channels joined together in a 2.80 m-wide reservoir or "water basin" enclosed by a large 2.45 m-thick wall, creating a second waterfall similar to the previous one (1.95 m high), although 10 m lower down. Of the two outlets that this reservoir had, the one closest to the "estolda" wall (central channel) was larger than the other (outer channel), with widths of 0.85 m and 0.45 m, respectively. The three canals finally converged in the outlet gully (still under the building) to carry the water through a buried conduit to the canal, downstream of the locks. The two inner canals were used to move the two water wheels, while the third canal (outer and narrower) was used as a spillway. The regulation mechanisms have been preserved, and they reveal the location of the three inlet "trampones", located inside the building (upper floor). There were also two other regulating mechanisms for the two conduits leading from the water tank. These mechanisms, located on the tank's closing massif, are not visible nowadays, since Fungairiño's project required the so-called "artefact chamber" to be irreversibly modified in order to install a turbine. The opening of the floodgates allowed each wheel to move independently and regulate its power. The first wheel moved a shaft that went through the "estolda" wall and ended in a lantern gear. This lantern gear engaged with a wooden crown gear with its camshaft (two sets of three cams each) demultiplying the speed of rotation to drive the bellows and achieving the cadence and continuity of blowing necessary to stoke the furnace fire and reach the necessary temperature. The bellows recovery system was based on a flexible pole with a rocker arm and anchoring arches (necessary to avoid collision with the cams of the shaft). The second wheel was set in motion when it was necessary to work the hot metal with the mallet. Its moving shaft had four cams that struck directly on the tail of the hammer; the hammer rotated around an axis or support that was firmly attached to a structure prepared to withstand the strong vibrations that were produced, forcing it to move in the same plane, without the possibility of lateral movements. With the existing network of channels next to the "stolda" wall and the identification of the "bergamazo" wall, the main rooms of the hammer mill are located (the "barquines room" and the mallet room), and with them, the two hydraulic wheels (of "Vitruvian" type). The diameter of these (approximately 3.00 m) was determined by taking into account the floor and ceiling heights of the lower body of the pile driver, as well as those of the water in the cistern and the "socaz". This result, somewhat lower than that proposed by Villa-Real (1736), is in line with the diameter of the wheels of other forges studied. The width of the wheels, to that of the channels (0.85 m), was approximately 0.6 m (Figure 12).

For the bellows room, the direction of rotation of its wheel (driven from below) and the height of the movement shaft "with respect to" the furnace, allows us to intuit the mechanism necessary to drive the wafers from above (Figure 13). The shaft (with three cams as in most of the forges analyzed) needed to reverse its rotation using a lantern-crown gear system. This system had the added advantage of reducing the shaft's rotational speed to produce a slow, gradual, and as continuous as possible emptying of the air from the bellows. The machinery was completed with a system for recovering the barges based on flexible poles, the most reliable and widespread in the 18th century and, at the same time, compatible with the location of the stairway in the barge room (stairway that gave access to the upper room, above the body of water, where the mechanisms for maneuvering the "trampones" or gates of each channel were located) (Figure 14).

Regarding the mallet room (Figure 15), with double height to dissipate the enormous heat generated in the furnace stoked by the bellows, it had a large chimney over the forge. The forging hammer was located directly in front of it to minimize the distance travelled with the red-hot iron billet. The hammer, which would be perpendicular to the four-cam shaft and must be driven by the tail, could have dimensions, elevation ratios, and weights similar to other hammers (Table 6). It was therefore a hammer for small pieces, also known as a "minor forge" or "tiradera", where castings of up to 57.5 kg were made to reduce them to billets or long bars with mallets of smaller dimensions than in the larger forges, where masses of up to 184 kg were cast (Villa-Real, 1736) [50]. Certain inventories, such as the one of 1851, describe this forge, which is no longer in use, with its layout, rooms for the employees on the upper floor and, with regard to the machinery (nowadays it is missing), they refer to the "water basin for the movement of the machines", of which only a wheel with its axis of movement and some bellows in the first body or ground floor remain at that date. The study of many forges in the north of Spain could lead us to think that the defining element of this typology, the "antepara" or raised water tank to move the gravity-type wheels, was also present in this case, but both the difference in level of this lock and the documentary sources have ruled out this hypothesis and finally lead us to a different and unique forge.

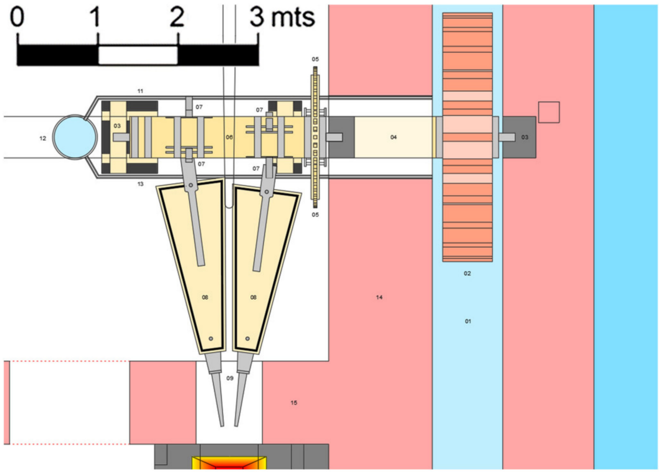
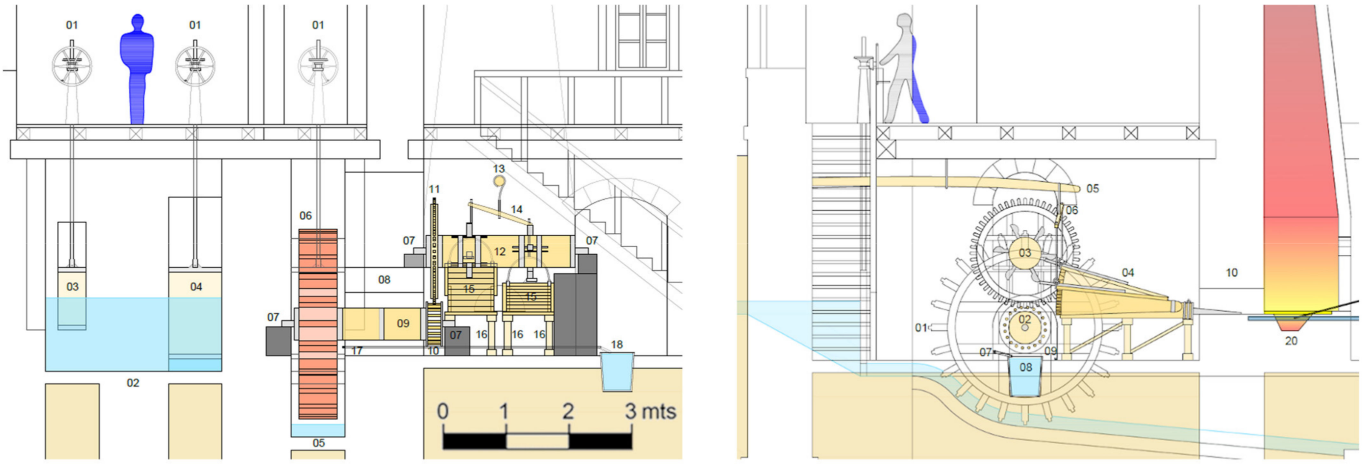


Figure 13. Detail of the bellows room of the forge. Source: own elaboration.



01 - GATES MANEUVERING
02 - WATER RAFT
03 - DRAINAGE GATE
04 - MALLET WHEEL GATE
05 - BELLOWS WHEEL CHANNEL
06 - WATER WHEEL
07 - AXLE SUPPORT
08 - WALL OF THE "ESTOLDA"
09 - WHEEL AXLE

10 - LANTERN GEAR
11 - CROWN GEAR
12 - CAMSHAFT
13 - FLEXIBLE WOODEN POLE
14 - DOUBLE-HOOK ROCKER
15 - BELLOWS
16 - BELLOWS SUPPORT
17 - WATER CHANNEL FOR THE BUCKET
18 - BUCKET FOR REFRESHING TOOLS

01 - WATER WHEEL
02 - WHEEL AXLE AND LANTERN
03 - CROWN GEAR AND CAMSHAFT
04 - BELLOWS WITH NOZZLES
05 - FLEXIBLE WOODEN POLE
06 - DOUBLE-HOOK ROCKER
07 - WATER CHANNEL FOR THE BUCKET
08 - BUCKET FOR REFRESHING TOOLS
09 - DRAINAGE CHANNEL
10 - "BERGAMAZO" WALL
20 - FURNACE AND CHIMNEY

Figure 14. Bellows room. Source: own elaboration.

Table 6. Hammer characteristics. Source: own elaboration.

Mallet	Compludo	Navafría	Taramundi	Alar
Handle Length (m)	3.92	4.60	2.75	3.64
Tail Length (m)	1.25	1.60	1.25	1.33
Elevation ratio	2.14	1.88	1.2	1.74
Weight (kg)	-	200	-	200

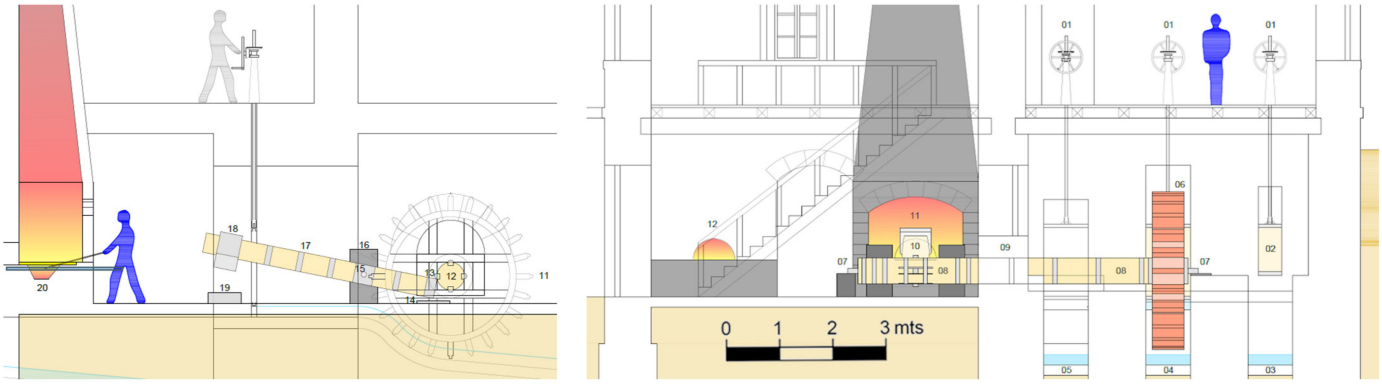


Figure 15. Handle room. Source: own elaboration.

The main difficulty encountered was the interpretation and reconstruction of the original body of water due to its, in the words of the engineer Fungairiño in 1922, special and "strange network of intake and drainage channels that exists, and which undoubtedly responded to the special needs of the industry to which the building was once dedicated (. . .)". Without knowing the shape of the original water body, it is impossible to correctly locate the specific machinery (wheels and hammer) of the forge. The relationship between the machines and the water body of the building is intimate and inseparable; it is not possible to understand either of the two elements separately, fully justifying the concept of the artefact. Secondly, the stage of synthesizing all the information in order to locate the machines correctly was particularly complex. It was necessary to identify the key walls (the stolda and the bergamazo), the two main rooms of a forge (existing in all the metallurgical establishments of the 18th century), and, therefore, the position of the two waterwheels in the two channels near the workshop.

The approach used in this study could be applied to other artefacts from the Canal de Castilla, adapting each stage to the new industrial process in question. Thus, for example, when a fulling mill is detected as the initial use of a canal artefact from historical documentary sources, it would be necessary to study the processes related to the fulling of the cloths, to know the evolution of the technology and machinery associated with this process and to analyze different examples of existing fulling mills in Spain. This is just the same for a flour mill, for a paper mill, or for any other industry of the canal.

The limitations of the results obtained in this study are related to the available data of the artefact. In this sense, the applied methodology, although it considers the uncertainty in the process of evaluating the alternatives and selecting the artifact reconstruction alternative that best suits the studied data, presents the limitations associated with the proposed fuzzy model [60,61]. In addition, the fieldwork did not allow measuring and checking inaccessible dimensions and missing elements. Laser scanner and unmanned aerial vehicle photogrammetric surveys could allow measuring inaccessible dimensions [62]. This is an important step in developing an HBIM model of the artefact [63]. The development of an HBIM model can be useful to study a new use of the artefact. The BIM methodology is already mandatory in several projects with public administrations and can be helpful in the visualization and intervention of heritage buildings [18].

The 2D graphical information obtained in this work could allow reconstruction of the artefact's machinery, but a 3D digital model of the artefact is not already available. As shown in other studies [26,64–66], 3D digital models allow the construction of prototypes and the study and simulation of all mechanisms, their operating conditions, and work conditions. Additionally, it could be validated that its mechanical performance is the same as similar studies of other locks [64,67].

4. Conclusions

The combination of data from all the activities described in the Materials and Methods section was essential for intuiting the original and complete functioning of the artefact. The main contribution of this work consists of recovering the memory of a relevant element of industrial heritage that is about to be lost. Other examples of the Castilla Canal have already been lost.

The reconstruction of the missing machinery established a hypothesis consistent with the technological solutions of the end of the eighteenth century as well as with the ironworks studied and with the documentary sources consulted. A comparison with other metallurgical establishments showed that the Alar forge, in addition to being atypical in Castile, is of greater importance and has the following unique characteristics:

- Typology around a courtyard and larger dimensions;
- Integration of new functions (housing for employees and lockkeeper);
- Elevation in height and functional separation by floors (industrial/residential);
- Absence of "antepara" and integration of the body of water in the building;
- Use of channels and gate maneuvering mechanisms;
- The determination that the approach, dimensions, organization, and construction of the Alar del Rey hammer is closer to those of some "Manufacturas Reales" of the eighteenth century, with common characteristics presented. We can say that it was (unlike traditional establishments) a comprehensive, compact, and innovative project that sought to rationalize the organization of ironwork, improving and dignifying the working conditions of employees at the same time.

Following this work, the study and recovery of other artefacts from the Castilla Canal could be undertaken. However, the study carried out at the AGCHD shows the limitations of the documentary sources, such that, for some of them, it would be necessary to broaden the field of research.

This research has made it possible to document the artefact's original stage and to establish when and for what purpose it was built, what the first industrial process that took place in it was, and how the machinery with which it was equipped worked. With these data as a starting point, the subsequent uses should be investigated, and finally, initiatives should be launched to enhance the value of this building and give it a new use. This research is ongoing with the creation of 3D digital models of the machinery and workplaces, as well as an HBIM model of all of the industrial facility. The HBIM model will require the creation of families for the building that can be used in other similar buildings. All the digital information from the HBIM model could be used for a future intervention design to enable a new use of the building. The 3D digital models of the machinery and its workplaces will allow the study of the production process through simulations of its kinematics and ergonomic studies with the incorporation of a digital human model (DHM). All these models will allow us to understand and enhance the value of the artefact.

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