The Twenty-One Books of Devices and Machines: An Encyclopedia of Machines and Mechanisms of the 16th Century

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Abstract Progress in Engineering and Architecture has been decisive in the birth and duration of empires throughout History, and Mechanical Engineering has always played an important role. For long periods of the 16th and 17th centuries the Spanish Crown became the World's leading political and economic power, so extensive that in the domains of King Philip II, "the Sun never set".

The strategic interest in Mechanical Engineering became clear with the appearance of "The Twenty-One Books of Devices and Machines of Juanelo" (Anonymous (Los Veintiún Libros de los Ingenios y Máquinas de Juanelo Turriano, 1997)), whose compilation was ordered by King Philip II around the year 1570 [1]. Among other knowledge exposed, the book contains a large number of machines of the period. The devices and machines are classified according to its function, with a surprising number of pumps, mills, cranes and other machines, particularly those driven by water, wind-energy, gravity or animal traction.

H.-S. Yan, M. Ceccarelli (eds.), *International Symposium on History of Machines and Mechanisms*, DOI 10.1007/978-1-4020-9485-9_9,

This work sets out some reflections on the importance of this book and takes a detailed look at the main mechanisms and machines described, while making comparisons with similar devices of the period or those that may have had an influence on the contents.

Keywords Machine encyclopedia, Spanish crown, 16th Century, Twenty-one books

Introduction

The complex process of founding empires that has existed throughout History, has always been an object of study due to the profound political, economic, demographic, religious and social changes involved. It is important to point out that almost all empires have arisen out of a situation of scientific-technological superiority. Progress in Engineering and Architecture has been decisive in the birth and duration of empires throughout History, and Mechanical Engineering has always played an important role [2, 3].

Every empire has needed to develop communication and trade networks, advances in the means of transport, in the exploitation of agricultural and mining resources, and in the building of cities and infrastructures, so as to address the population's needs. In addition fortifications and defense structures needed to be continuously improved against potential enemies. In order to meet all these requirements, the use of efficient machinery and resourceful devices has always been paramount.

For long periods during the 16th and 17th centuries, the two Iberian empires became unified, whereupon the Spanish crown became the World's number one political and economic power, so extensive that in the domains of King Philip II, "the Sun never set".

In the framework of this empire a need arose for the Spanish Crown to have highly qualified professional experts at its disposal. The scarcity of which is made clear in a letter by Francés de Álava, written to Philip II in the second half of the 16th Century: "The persons that I know in Spain employed in the service of Your Majesty as qualified engineers […] are all foreigners and I know not a single Spaniard who knows anything as near as much as any of them".

The strategic interest in Mechanical Engineering became clear with the appearance of "The Twenty-One Books of Devices and Machines of Juanelo", whose compilation was ordered by King Philip II around the year 1570 and is nowadays preserved in the National Library in Madrid (www.bne.es). Among other knowledge, the book contains a large number of machines of the period. The devices and machines are classified according to its function, and a surprising number of pumps, mills, cranes and other machines, particularly those driven by water, wind-energy, gravity or animal traction is included.

It is regrettable that the book was not published at the time due to a lack of consent by Philip II. Had it been published, it would undoubtedly have become as

well-known as the most famous European Renaissance treatises. Known and probably used by engineers and architects such as Gómez de Mora, Teodoro Ardemans and Benito Bails, it remained in relative oblivion until the 60s of the last Century when various historians in Technology showed an interest in it.

This work sets out some reflections on the importance of this book and takes a detailed look at the main mechanisms and machines it describes, while making comparisons with similar devices of the period or those that may have had an influence on the contents.

On the Authorship of the Twenty-One Books

The School of Civil Engineering prepared an edition of "The Twenty-One Books of Devices and Machines" in 1983 and the Juanelo Turriano Foundation, founded by José Antonio García-Diego in 1987, produced a facsimile edition in 1997. However, the continuing efforts of publishers and researchers have failed to reveal the authorship of the codex.

Round about 1645, Gómez de Mora, the royal architect, chose the title page shown in Fig. 1 for "The Twenty-One Books", where it reads, "The Twenty-One Books of Devices and Machines of Juanelo". This reference to Juanelo on the title page contributed initially to Juanelo's being attributed the authorship of this work.

"The Twenty-One Books of Devices and Machines of Juanelo, ordered written and demonstrated by King Philip II, Catholic King of Spain and New World. Dedicated to John of Austria.".

Fig. 1 Title page of the Twenty-One Books

Later on, the words "Machines of Juanelo" was thought to be only a way of alluding to the quality of the machines described in the work, due to his renown at the time and the reputation that grew around him. Moreover, it seems strange that Juanelo Turriano would not include his most important work in this great Machine Encyclopedia: the famous device for raising water from the river Tagus

to the Citadel in Toledo, the old capital of Spain, overcoming a difference in level of ninety metres.

In view of the features of the text, written in a Spanish full of Aragonese expressions, with numerous and precise references to Aragón (Spain), José Antonio García-Diego and Juan Antonio Frago reached the conclusion that the author was of Aragonese origin but his identity remained still unknown.

After some additional and detailed research, Nicolás García Tapia put forward Pedro Juan de Lastanosa (1527–1576), from Aragón, as the author, an inclination that has gained strength in recent years. On the other hand, not everyone accepts this hypothesis, which has given rise to heated polemics that have promoted an even more extensive study of this work, which in turn has led to new studies being published on the matter [4–8].

A relevant argument contributed by Antonio T. Reguera, refers to the contradiction that Lastanosa left no proof of his authorship, when, for instance, his recognition as legitimate holder of a patent for a mill is well-known.

At present, various authors are of the opinion that "The Twenty-One Books" may have been written by different authors, one of whom would have been Lastanosa, according to Nicolás García Tapia's version. This hypothesis is supported by the existence of considerable differences between chapters of the work regarding style, degree of detail and scientific-technical quality.

New events have occurred recently that open up new lines of future research. María Teresa Cacho located an undated and unsigned manuscript preserved in the national Library of Florence, entitled "Trattato dell'acque". This is a treatise on Hydraulic Engineering written in Spanish that bears a remarkable similarity to "The Twenty-One Books" preserved in the National Library of Madrid. Much shorter with only 84 pages, it contains 350 illustrations of which 315 appear in the Madrid manuscript. The faint definition of some of the illustrations suggests that the Florentine version is older.

A third manuscript has also been discovered belonging to a private collection in Barcelona, and therefore less known than the previous ones. This Catalan Codex comes close to the Madrid version, having 609 pages and 404 illustrations compared to the 949 pages and 509 illustrations of the Madrid manuscript.

Structure and Contents of the Twenty-One Books

The compendium kept in the National Library of Madrid deals with numerous themes related to Mechanical Engineering, Civil Engineering, Naval Engineering and Architecture, as well as how to obtain and process different raw materials used extensively in these disciplines. All this knowledge is grouped together in five related books, following the structure set out below:

Books One to Five: On the properties of water, methods for finding it and evaluating its quality.

Books Six to Ten: On how to extract, transport and store water. On the construction of aqueducts, dams, cisterns and tanks.

Books Eleven to Thirteen: On mills, how to build them, the different types and their use for grinding corn, sifting flour, extracting water and washing fabric.

Books Fourteen to Eighteen: On the use of wood and stone for building. On the properties of these raw materials and how to obtain them. On the construction of stone and wooden bridges and boats.

Books Nineteen to Twenty-One: On building structures on the sea and about harbour defenses. On other works of Hydraulic Engineering and water clocks.

Below are listed the main developments described concerning Mechanical Engineering, together with a comparative study of other similar inventions existing towards the end of the 16th Century, when this Machine Encyclopedia was produced.

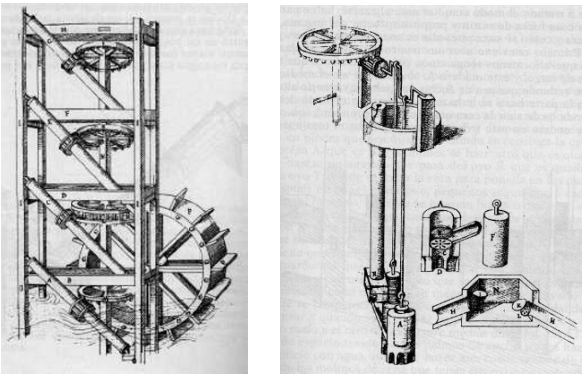
Some of the Main Devices and Machines Included in the Twenty-One Books

These Books include detailed descriptions of machines and devices, mainly water raising machines, different kinds of mills and building machinery; in order to give this work a practical character according to its historical context.

Water Raising Machines

The need to supply cities with water together with the requirements to remove water from mine workings, especially in the territories in the Viceroyalty of New Spain, promoted the compilation of many references to hydraulic devices such as pumps, and to water raising devices in general.

Some references are about improvements to machines known and used since Antiquity. Figure 2a shows a set of four Archimedes screws driven by a common hydraulically powered shaft, with a remarkable water-raising capacity. Figure 2b shows a crown-lantern gear that drives a crankshaft to power a force pump similar to Ctesibius', which works by alternately sending a flow to a collector tank from each of the two compartments in which the pump is divided. Due to this principle, a more uniform flow is obtained since the two pumps take turns to raise the water, which flows out through some side openings in the pistons themselves.



a) b)

Fig. 2 (a) Archimedes screws; (**b**) Force pump; from "The Twenty-One Books"

The text of "The Twenty-One Books" recommends using these pumps for raising water to great heights, but only in small amounts due to the weight of water. Also emphasized is the importance of using the correct size machine parts.

Figure 3 shows other water raising devices, this time animal-powered, which provides information as to the size and power of the machines.

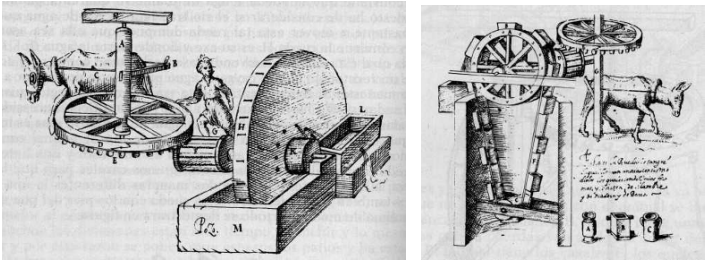
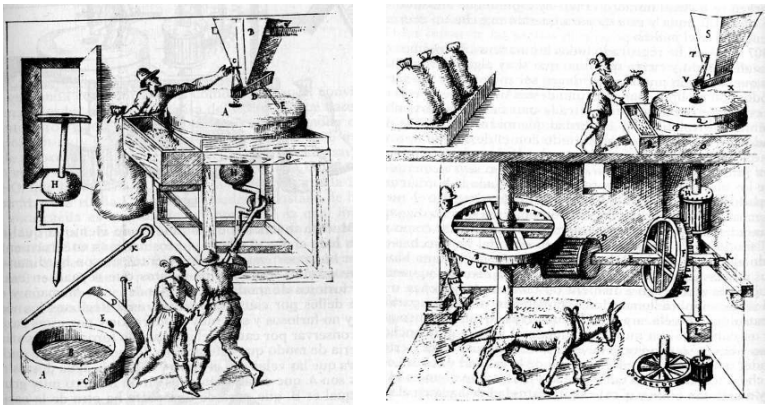


Fig. 3 Animal-powered water raising devices, from "The Twenty-One Books"

Iberian Empire Mills

Milling was of vital economic importance in these first colonial empires, because various sectors of industry and agriculture depended on it. Wheat and oil were the staple diet of the native population of the Iberian empires. In addition, mills were linked to colonial mining and therefore to the financial support of the conquering and expansion activities.

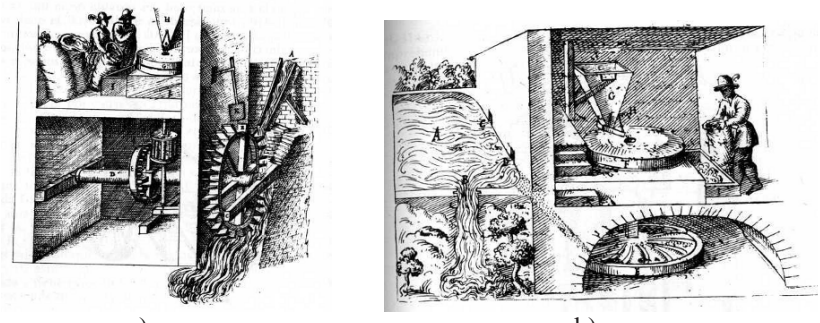
The descriptions found in "The Twenty-One Books" start out from some simple mechanisms like the hand-operated flour mill in Fig. 4a, or the animal-powered one in Fig. 4b.



a) b)

Fig. 4 Flour mills from "The Twenty-One Books"; (**a**) Hand-operated; (**b**) Animal-powered

Hydraulic power drive is also frequently described, using both vertical wheels (Fig. 5a) and horizontal wheels (Fig. 5b). There is a section in "The Twenty-One Books" devoted to a study of the appropriate layout and spatial location for water pipes carrying water to the wheels so as to improve operating efficiency.



a) b)

Fig. 5 Water wheel-driven flour mills, from "The Twenty-One Books"; (**a**) Vertical wheel; (**b**) Horizontal wheel

On other developments explained the mill is driven by wind-power, as in Fig. 6, which the writer assures, "is very common in Flanders, Germany and France, but not in Spain or Italy because the winds in these regions are not suitable for driving them as they are not constant when they blow".

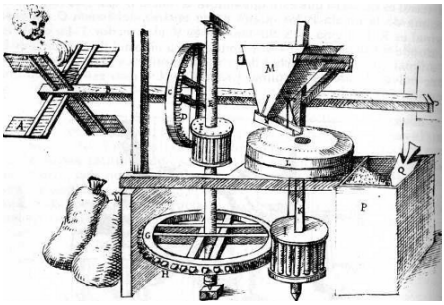
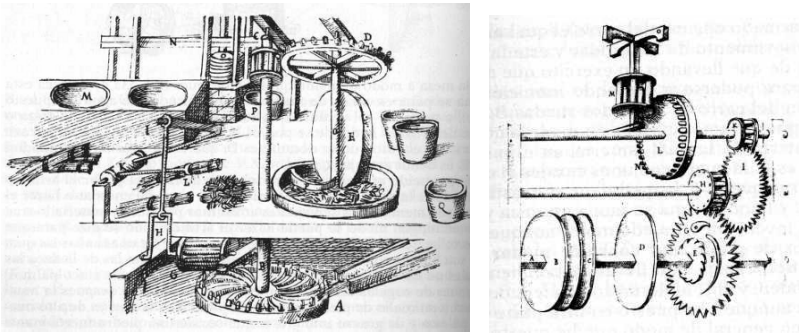


Fig. 6 Windmill, from "The Twenty-One Books"

When sugar cane began to be exploited overseas, milling machines were also required, which led to the development of more complex high production systems. The set up shown in Fig. 7a presents a drive wheel that in turn powers the milling and automatic sugar cane cutting mechanism, enabling the cutting and milling operations to be synchronised.

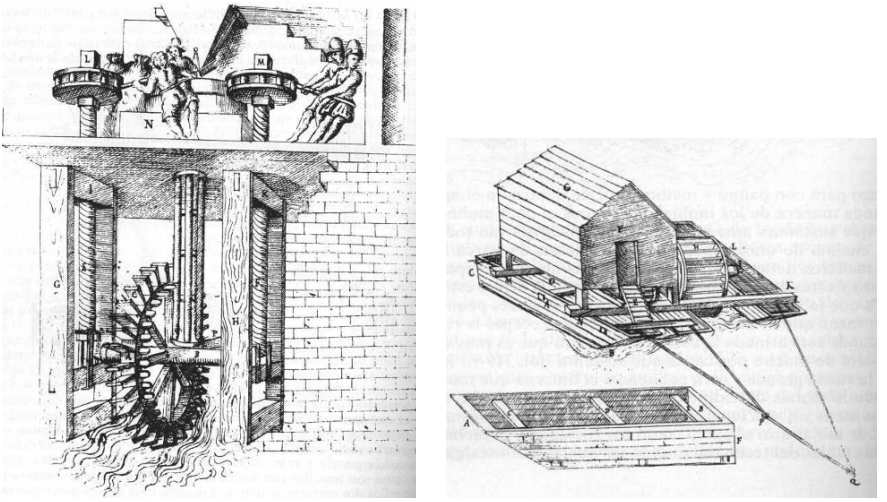
The attempts to develop ever more productive mills becomes clear in other machinery presented in the text, like the device shown in Fig. 7b for milling flour. The author himself warns that the high efficiency means that the parts may often suffer damage. The transmission mechanism is more complex, with three horizontal shafts, one vertical and including several reduction stages. Also noteworthy is the addition of fly wheels and a ratchet mechanism on one of the wheels. This mill with counterweights gave rise to litigation, concerning patent rights, between the Spaniard Pedro Juan de Lastanosa and the New World Spaniard Ruy Lope de Luna, which ended in a judgement of Solomon with the profits being divided between both of them.

Moreover, the machine in Fig. 7b works with counterweights, using large weights set at a considerable height. It is an example of the efforts made in the 16th century to use not only animal or hydraulic energy but also gravity, as additional support.



a) b)

Fig. 7 (**a**) Mill for producing sugar; (**b**) High efficiency flour-milling mechanism, from "The Twenty-One Books"



a) b)

Fig. 8 (a) Flour mill adjustable to the level of flow of the water; (**b**) Floating mill

Another way of improving productivity was to endow the machines with a capacity to work in more demanding conditions:

Figure 8a shows a flour mill that can be adjusted in case the wheels are powered by highly changing currents. In such a situation, it is useful to be able to adjust the height of the water wheel and to adapt the position of the paddles according to the water level, which was performed by operating two screws. The great length of the lantern means that it will always engage the crown mounted on the water wheel although its height may vary.

Figure 8b shows floating flour mills that the author of "The Twenty-One Books" claims to have seen in many parts of Italy. The anchorage allowed them to be adapted to the amount of water of the river. The wheels powered by water from beneath had to be placed in pairs or be wider than other types of mill wheels, since the slow running water often did not provide enough power to move them. Consequently, it was quite usual for them not to be able to grind much grain, unless they were driven on fast-flowing rivers.

"The Twenty-One Books" include new designs based on grouping together other devices and discuss the feasibility of these novel designs. One example of this is the sophisticated machine shown in Fig. 9, which performs numerous tasks at the same time: crushing gunpowder, polishing and cleaning weapons and milling flour.

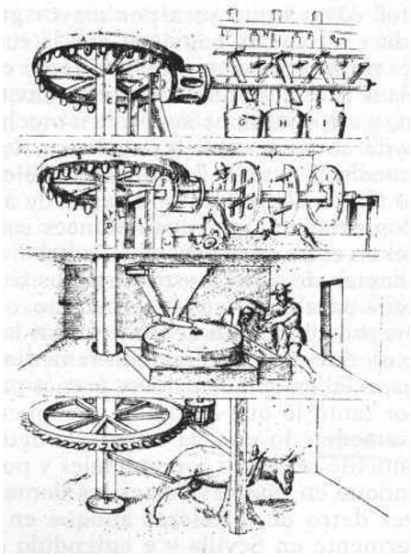


Fig. 9 Machine for performing numerous operations simultaneously, from "The Twenty-One Books"

Building Machinery

The great works of architecture carried out in the age of splendour of the Iberian Empire also required lifting machines with important mechanical requirements. "The Twenty-One Books" contributed to the spread of some of these cranes, like the one in Fig. 10, used for lifting building workers in a kind of cage. Elevation was achieved by some manually operated drums that took up the rope using a pulley system. It could also be used for lowering persons, down to mining galleries, for example. Other different cranes are depicted in Fig. 11.

The text sets out the advantages of using pulleys and multiple ropes to reduce the weight borne by each cord when lifting very heavy weights.

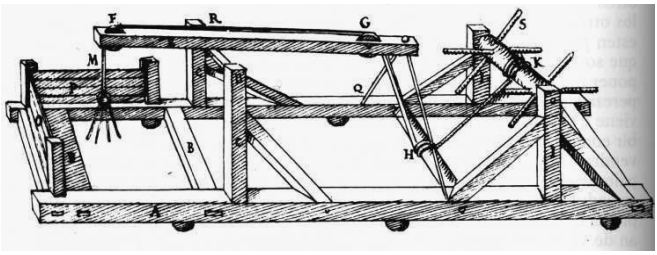


Fig. 10 Machine for lifting and lowering workers

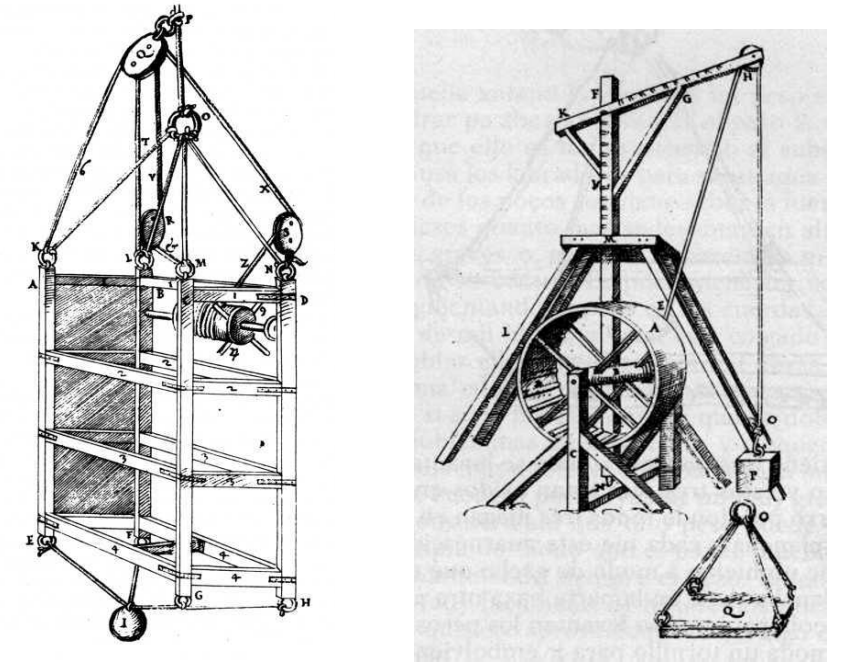


Fig. 11 Cranes, from "The Twenty-One Books"

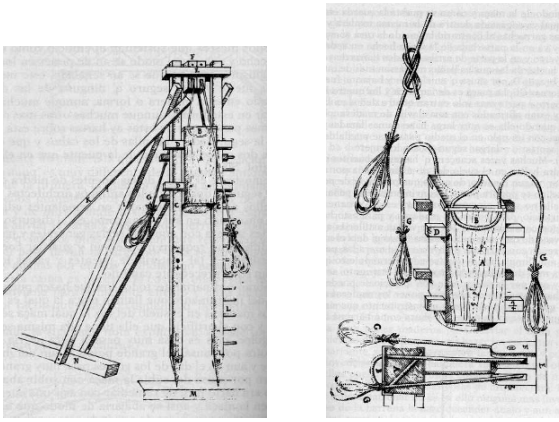
Other Machines and Mechanisms in the Compilation

It is difficult to summarise the contents of the "Twenty-One Books of Devices and Machines" in relation with other types of devices and machinery, which is why only a few examples are given below.

Overseas relations meant that harbours had to be enlarged and in many cities built. Pile driving machines were frequently used in the period; Fig. 12a depicts one of the machines of this kind explained in these books. It was manually operated by pulling on ropes to raise the hammer with the use of pulleys. The way of joining the ropes to the pulleys and hammer is shown in detail in Fig. 12b.

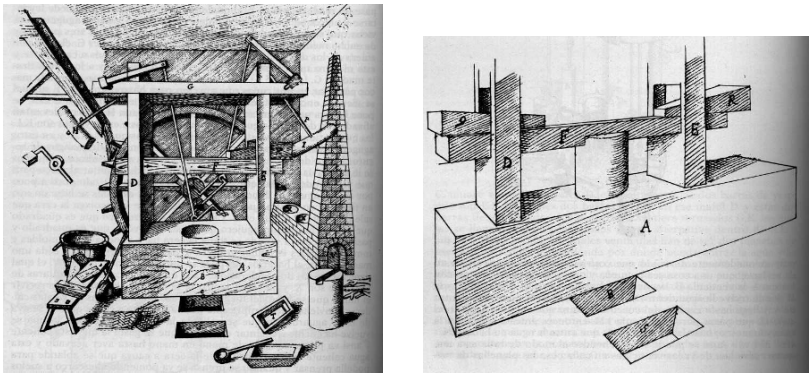
The machine in Fig. 13a consists of a hydraulic press, with a crankshaft to drive an articulated rod mechanism. These move some swing hammers that strike a wedge to produce pressing by means of a crossbeam. The machine can be seen in operation in Fig. 13b.

Another device shown is one for beating and washing clothes with water, as in exposed the diagram of Fig. 14. A small flow of water halfway up a water wheel suffices to set the device in motion, by producing movement in a shaft bearing two radial actuators to act as cams to cause the pendulum motion of the washing tools.



a) b)

Fig. 12 (**a**) Pile driving machine; (**b**) Detail of the device, from "The Twenty-One Books"



a) b)

Fig. 13 (**a**) Wax press; (**b**) Detail of pressing, from the Twenty-One Books

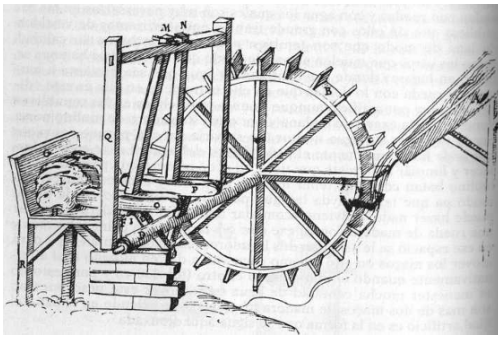


Fig. 14 Clothes washing device, from the Twenty-one Books

Comparison with Other Machine Treatises During the Renaissance

The Machine Renaissance, starting from Italy, reached extent areas of Occidental Europe in the second half of the 15th century, where the development of relevant machines and devices rose very quickly. The main developments were hydraulic devices, mills, building machinery and other useful machines, in line with the machines included in "The Twenty-One Books". Nevertheless, the interest in other less practical devices such as clocks or automatons was reduced [9].

The treatises of the Renaissance include mainly new machines and reviews of past works in order to improve their capacity, accuracy and efficiency. For example, though the Archimedes screw is supposed to be known and used since the Antiquity, this system was reproduced later in many works during the Renaissance [2], like shows the Fig. 15a depicted by Daniele Barbaro in 1584 or the cited modification of this machine presented in the Twenty-One Books (Fig. 2a). Other hydraulic devices included in the Twenty-One Books (Figs. 2b and 3), show correlations not only with machines from the European culture but also with preceding illustrations from Medieval Islam [10]. For example, the machines of Al-Jazari reveal a high interest in hydraulic machines, like the one depicted in Fig. 15b, from Al-Jazari's "Book of Knowledge of Ingenious Mechanical Devices", finished in 1206. In addition, Di Giorgio's "Trattati di architettura ingegneria" ("Architecture and machines treatise") published in 1484, includes examples of water suction machines like the hand-operated dual piston pump depicted in Fig. 16 which reminds the pump shown in Fig. 2a.

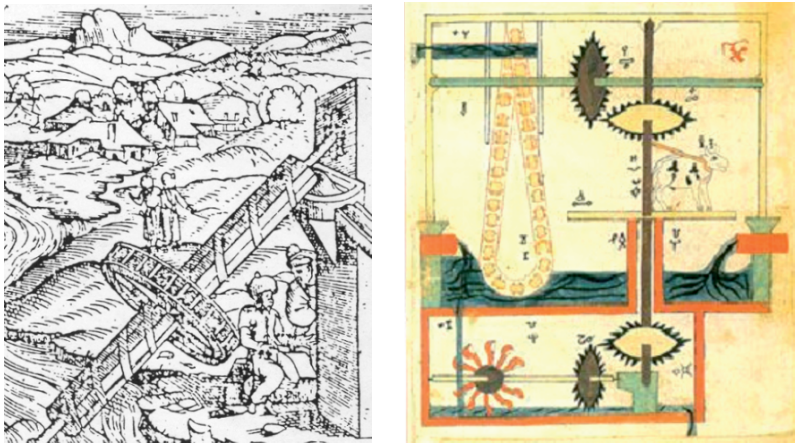


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Fig. 15 (**a**) Archimedes screw, by Daniele Bárbaro (1584); (**b**) An hydraulic machine from Al-Jazari's book

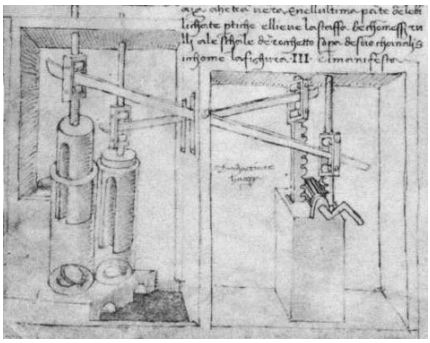
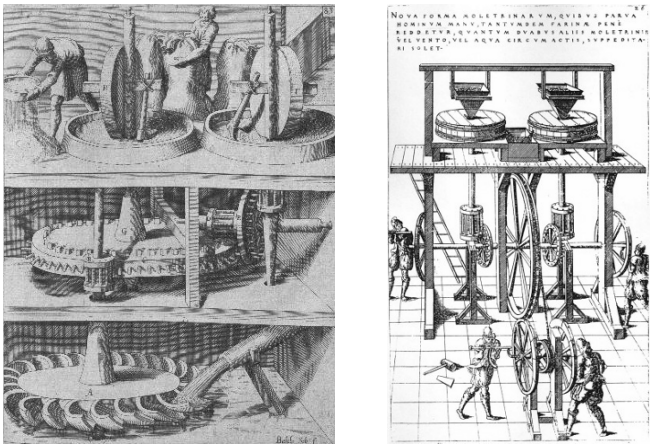


Fig. 16 Di Giorgio's water suction machine from "Trattato di architectura e machine"

In the same way, the mills included in "The Twenty One Books", like the examples shown in Figs. 4, 5, 6, 7, 8 and 9, bear numerous similarities to other Renaissance works. A remarkable example due to Jacobus Strada is the flour mill in Fig. 17a included in his work "Kunstliche Abrís allerhand Wasser – Wind Rosz- und Handt Muhlen" from 1617 [2]. In this new design some considerations have been taking into account in order to enhance previously existing designs. On the one hand, a horizontal water wheel is used, which constitutes an authentic turbine with spoon-like blades designed so that the flow will hit the blade and leave in the precise direction to obtain the maximum efficiency. On the other hand, the machine is improved for proto-industrial applications, by using a large horizontal tooth wheel and two lanterns, in order to distribute the power transmitted to two different mill wheels. Another example is shown in Fig. 17b concerning a hand-operated mill with two mill wheels, included in Jacobus Bessonus's "Theatrum Instrumentorum et Machinarum", published in 1578 [2].

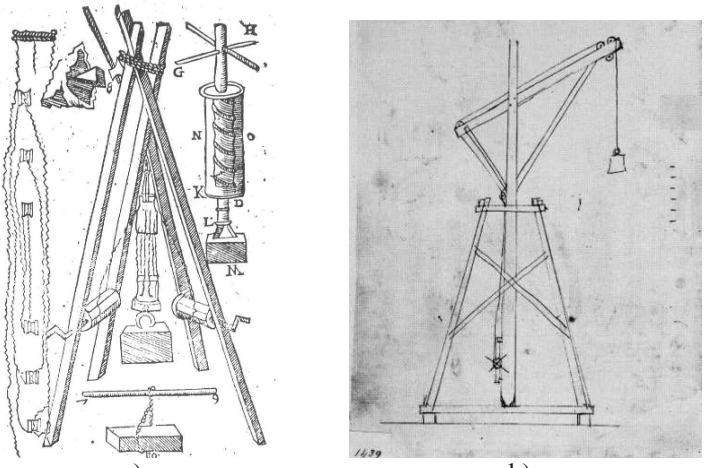


a) b)

Fig. 17 Mills by renaissance authors; (**a**) Jacobus Strada; (**b**) Jacobus Bessonus

The same considerations regarding technical solutions similar to other authors are common in the chapters of "The Twenty-One Books" devoted to lifting machinery for building applications. The appearance of the devices shown in Figs. 10 and 11 reminds for example a machine depicted by Daniele Barbaro in 1584 (Fig. 18a), considering the comments in Vitruvius' book "De Architectura" [11,12] and a machine scheme (Fig. 18b) present in Antonio Da Sagallo's collection of sheets from 1526 approximately [2].

It is possible to find many additional examples of machines with equivalent mechanical developments in other Renaissance and Pre-Renaissance works [2,13,14].



a) b)

Fig. 18 (**a**) Vitruvius' elevator represented by Daniele Barbaro; (**b**) A crane, by Antonio da Sangallo

Finally, the similitude between many devices included in "The Twenty-One Books" and other remarkable manuscripts of the Renaissance is shown through the Figs. 12, 13 and 14, compared respectively to the pile driving machine shown in Fig. 19, the press depicted in Fig. 20a and the washing device shown in Fig. 20b. Figure 19 has been taken from Giovanni Branca's "Le machine" from 1629 [15]. Figure 20a,b have been obtained from Zonca's work [16] entitled "Novo teatro di machine et edificii "written in 1607.

The machines found in "The Twenty-One Books" are in line with many other remarkable books of the Renaissance, though some designs exposed are simpler than those of Strada, Bessonus or Branca. The major contribution of "The Twenty-One Books" is the compilation, as a kind of Machine Encyclopedia, of many useful machines and devices used at that time in several application areas and for numerous practical tasks. The dissemination of the machines is highly promoted with this compendium, because of the detailed figures and comments on each one of the hundreds of designs exposed, including guidelines for the construction, comparisons between machines, advantages and disadvantages of each design.

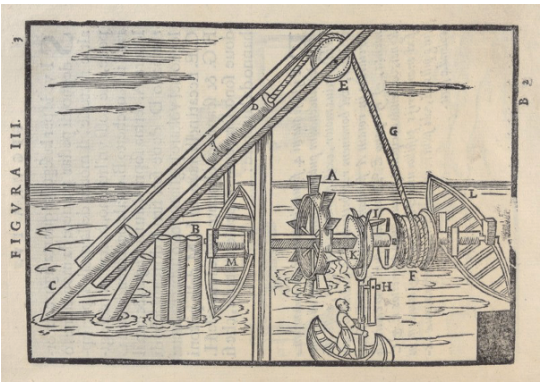
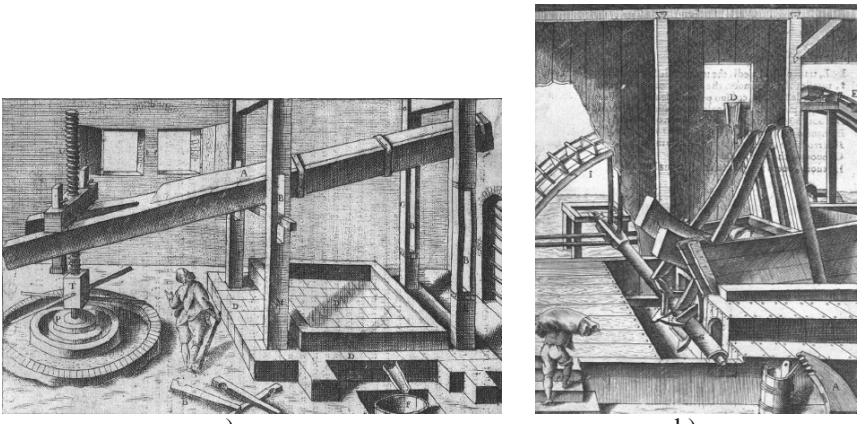


Fig. 19 Pile driving machine by Giovanni Branca, from "Le machine"



a) b)

Fig. 20 (**a**) Zonca's press; (**b**) Zonca's washing device; from "Novo teatro di machine et edificii"

Conclusions

The "Twenty-One Books of Devices and Machines" is the first and most important Encyclopedia of Machines and Mechanisms written in Spain. It was ordered to be written by King Philip II around the year 1570, as a sign of the strategic interest that Mechanical Engineering has always had in the birth, expansion and defense of any empire. This work sets out some reflections on the importance of this book and takes a detailed look at some of the main mechanisms and machines described, while making comparisons with similar devices of the period or those that may have had an influence on the contents.

Despite the fact that most of the machines and mechanisms described in "The Twenty-One Books" do not represent any significant technological progress regarding to devices already existing at the time, the large number of themes dealt with and their detailed analysis is remarkable. Additionally, the detailed schematic drawings included in "The Twenty-One Books" provide insight on the size and power of many different machines of the 16th century. It was undoubtedly written as a reference for all the engineers of the Spanish Crown for providing advised on how they should optimize their tasks with the help of Machines and Mechanisms.

Who wrote, copied, edited or compiled this compendium of Engineering and Architectural Knowledge is really of no special importance; what really bears relevance is that the manuscript has been preserved. Therefore we can continue its detailed examination and many of the devices and machines described can even be reproduced, thanks to the high level of detail devoted to its production.

We hope the reflections exposed help to call the attention, of foreign specialists on History of Machines and Mechanisms, on the largest compendium produced on this subject in Spain. We also would like to increase the technological and teaching interests on the machines and devices explained in the work.

References

1. Anonymous (1997) Los Veintiún Libros de los Ingenios y Máquinas de Juanelo Turriano, Facsimile of the manuscript (circa 1570) in the National Library in Madrid, Fundación Juanelo Turriano.
2. Bautista E, Ceccarelli M, et al. (2007) Breve Historia Ilustrada de las Máquinas, Sección de Publicaciones de la E.T.S.I.I. Universidad Politécnica de Madrid.
3. Kaiser W, König W (2006) Geschichte des Ingenierus: Ein Beruf in sechs Jahrtausenden, 150 Jahre Verein Deutsche Ingenieure 1856–2006, Carl Hanser Verlag.
4. García Tapia N (1994) Ciencia y Técnica en la España de los Austrias, Una visión desde la perspectiva de las investigaciones actuales, Cuadernos de Historia Moderna, Editorial Complutense, Madrid.
5. García Tapia N (1990) En Defensa de Lastanosa, Revista de Obras Públicas.
6. García Tapia N (1989) Técnica y poder en Castilla durante los siglos XVI y XVII, Consejería de Cultura y Bienestar Social.
7. García Tapia N (1988) Pedro Juan de Lastanosa y Pseudo Juanelo Turriano.
8. García Tapia N (2001) Un inventor navarro, Jerónimo de Ayanz y Beaumont, Departamento de Educación y Cultura de Pamplona.
9. García-Diego JA (1982) Los relojes y autómatas de Juanelo Turriano, Albatros.
10. Hill D, al-Hassan A (1986) Islamic Technology: An Illustrated History, Cambridge University Press, Cambridge.
11. Ortiz y Sanz J (1787) Tratado sobre máquinas de Vitruvius.
12. Vitruvius PM (1511) De architectura. Published by Fra Giocondo, Verona. (reprinted in 1513, 1522 and 1523)
13. Banu Musa, The book of ingenious devices: Kitab Al-Hiyal, 10th Century.

14. Al-Yazari, Al-Zaman B, Hill D, (1974) The Book of Knowledge of Ingenious Devices, D. Reidel Publishing Co., Dordrecht.
15. Branca G (1629) Le machine.
16. Zonca V (1607) Novo teatro di machine et edificii per uarie et sicure operationi, Appresso F. Bertelli.