



# Mechanical Wits Used in the America Colonization: Engineering Assessment

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## Abstract

The first European settlements in the new world faced technical issues with the help of the XVI century scientific advances. Besides briefly exposing the scientific and technological situation, this paper explores, with the help of reverse engineering, two singular mechanical wits representative of the technological advances introduced in America to overcome different problems. Firstly, a pump, based on an alternative movement system through crankshafts and pistons used against the continuous flooding suffered in the Ciudad de México valley. Although flooding remained a problem (it was solved in the XX century), hydraulic pumps were essential for continuous soil drainage. Secondly, a port crane for handling cannons, military devices, and construction materials during the Lima fortification in the XVII century. For both cases, reverse engineering, through engineering methods, Computer-Aided Design CAD programs, and additive manufacturing, provides virtual and/or tangible mockups that help to analyze and improve our knowledge about the dimensions, materials, and functions of used (and currently lost) mechanical systems during the American colonization.

**Keywords** Port crane · Hydraulic pump · Reverse engineering · Industrial heritage

## 1 Introduction

Europe's technological and scientific advances during the XV and XVI centuries were critical for developing agriculture, metallurgy, warfare, and naval transport (Prieto Romero, 2009). The printing press played an important role in increasing the possibility of expanding the wealth of existing knowledge to extraordinary levels in a society that already had a large amount of graphic production. Each improvement feedbacked the others and was boosted by the trade routes in the Mediterranean Sea, the opening of routes between East and West, and finally with the New World.

Innovations in agricultural technology were unevenly lodged in Europe. These advances include using better water mills to drain the land, employing drying techniques, and obtaining a balance between crops and animals, with a method consisting of cultivating a specific part

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of the land to feed the animals and fertilizing the land. The insertion in Europe of new crops from America and Asia required new engineering knowledge to drain the land and set up new farms.

From the middle of the XV century, Germany laid the foundations for mining exploitation and subsequent metal processing by improving mining techniques. At that time, Germany had some of the richest mines. During the first half of the XVI century, a growing transfer of mining and metallurgical technology took place in two directions: in America, to exploit the silver mines of Potosí and Mexico, and Central Europe (Prieto Romero, 2009).

Other metallurgical procedures were undergoing improvements, such as the melting of metals, contributing to the latest advances in Chemistry by providing experience on chemistry empirically, since to use this science was necessary to have complete and precise control of the metals and non-metals that intervene in it.

Following the above discussion, from XV to XVIII centuries, the Spanish settlement of colonies in America required a critical scientific and technological effort to solve many technical issues (Calvo & Enoch, 2005). Nevertheless, the details of these solutions are currently unavailable due to the secrecy and vertical knowledge based on petitions from vassals to the king was the preferred way for scientific documentation in the Spanish empire (Canizares-Esguerra, 2018). This approach did not reduce scientific creation, but it has contributed to hiding many technical advances and scientific developments achieved by Spanish and Native Americans.

According to the above paragraph, there is a noteworthy lack of tangible remains and historical references that help to value and appreciate the engineering quality of the used mechanical solutions during the American colonization. A way to overcome this knowledge gap is using reverse engineering (Montes et al., 2016; Torres-Garrido et al., 2019). Through engineering procedures, software programs such as Computer-Aided Design CAD software, and additive manufacturing, this methodology provides virtual and scaled mockups useful to obtain information about materials, dimensions, and kinematic and mechanical behavior of mechanical systems.

The reverse engineering procedure explained in this work was used to get virtual models and scaled prototypes of two devices: a pump used to drain the Ciudad de México valley during the XVII century and a port crane used for handling goods in the port of Lima in the XVIII century. Despite the difficulties raised by the secrecy pointed out above, engineering methods supported by current Computer Aided Design CAD programs, numerical simulation tools, and rapid prototyping can improve our knowledge about these ancient technical wits.

Regarding the manuscript structure, Sect. 2 explains the reverse engineering procedure mentioned above. Then, Sects. 3 and 4 are devoted to describing how the procedure described in Sect. 2 can be practically applied to analyze the hydraulic pump, and the crane mentioned previously. Specifically, Sects. 3.1 and 4.1 detail the procedure for the hydraulic pump and the crane devices in the spotlight. On the other hand, Sects. 3.2 and 4.2 summarize and show the resulting virtual models and/or mockups. Finally, the main conclusions are drawn in Sect. 5.

## 2 Reverse Engineering Procedure

Reverse engineering (hereafter also RE) aims to obtain a model and/or information regarding an existing product. It is based on a detailed product study to identify materials, components, dimensions, and performance under its usual operating conditions.

RE can help to recover the technical knowledge of the past. Nevertheless, the methodology has to be adapted because there are few physical examples or any at all. Besides, references to old devices are usually focused on their social or historical impact instead of on a technical description. Finally, even technical descriptions are limited, so to reproduce a mechanical solution's operation, it is necessary to make assumptions based on engineering experience.

This paper proposes a simple reverse engineering procedure adapted to recover mechanical devices that tackle the above drawbacks. The procedure is simple and based on the following steps:

*Step 1* Look for information sources. Information is sorted from more to less attractive: Genuine ancient artifacts, references that give technical hints, and references that include historical descriptions.

*Step 2* Identify components and fill the gaps. Connect the information extracted from the sources, and identify materials, components, and sub-systems. Knowledge gaps can be filled by studying the engineering techniques applied in the product's historical period.

*Step 3* Obtain the components' dimensions. Dimensions are needed to obtain a virtual model. If there is a physical example, dimensions can be measured; otherwise, dimensions must be estimated from technical texts, schemes considering that de components are represented proportionally, or the assumed mechanical system operation.

*Step 4* Study the system kinematic. System movement is essential to understanding how it works. Once components' links and dimensions are known, it is possible to build a CAD model of the system and use CAD tools to analyze its kinematic.

*Step 5* Study the system performance. Test the model to evaluate its response to assumed used conditions. This step is open to structural and energy analysis.

*Additional Step* Build a demonstrator. A virtual and/or a scaled mockup can help further understand how the system works and its possibilities.

The above procedure is applied to study two different mechanical wits that could have been used during the Spanish colonization.

### 3 A Draining Wit

In 1521 the Spanish settled Mexico City in the 9 square kilometer area formerly known as Tenochtitlan. Unfortunately, the city is located in a valley that suffers continuous floods.

There are many historical events related to the flooding problem explained, for example, by Catalá (1994). A detailed explanation of all events exceeds the limits of this study. Nevertheless, the following paragraphs summarize the most relevant technical approaches to solve the problem.

According to the writings (Catalá, 1994), on October 14, 1555, the Cabildo (the responsible for the municipality's government) requested a solution to the water problem. Viceroy Velasco ordered the rebuilding of the stones works destroyed in the past, but that solution did not solve the problem.

In the absence of short-term solutions, the viceroy proposed changing the location of the city, to which Madrid replied that it would cost more to build the capital from scratch than to solve the flooding problem. Therefore, it was needed to find a quick and effective way of drainage to continue facing the problem of the works. This task was designated to

the engineer Enrico Martínez, who had the ingenious idea of draining the valley by drilling it to leak the formed lagoons' water.

After successive and unsuccessful attempts to continue with his initial idea, Enrico Martínez was accused of negligence and taken to prison. However, he was finally released to participate in the project again because of his experience. When Enrico Martínez died in 1630, Fray Andrés de San Miguel, a Spaniard living in Mexico, accepted the challenge. He had excellent knowledge of hydraulics, knew the previous solutions, and supported ideas such as the open-pit excavation of the drainage pipe and the use of mechanisms to drain the valley.

The viceroy faced desperate of the flooded capital situation, also supported the above idea, and ordered the Cabildo to promote a drainage system and boosted the project with 24 machines and the necessary men and animals for continuously evacuating water in strategic points of the city.

It was not until the twentieth century, when the continuous drainage of the subsoil motivated by the increase in population, meant the end of the water problem. The initial drainage piping idea, more than draining the valley, served to control the level of the surrounding lakes and was never finished due to the continuous government changes and the non-continuity of the works.

The continuous extraction of water from the subsoil during the colonial period was critical compared to the failed project for controlling the lakes' water through drainage pipes. Thus, the recovery and technological analysis of a hydraulic pump used at that time for draining water are interesting.

### 3.1 Reverse Engineering: Hydraulic Pump Reconstruction

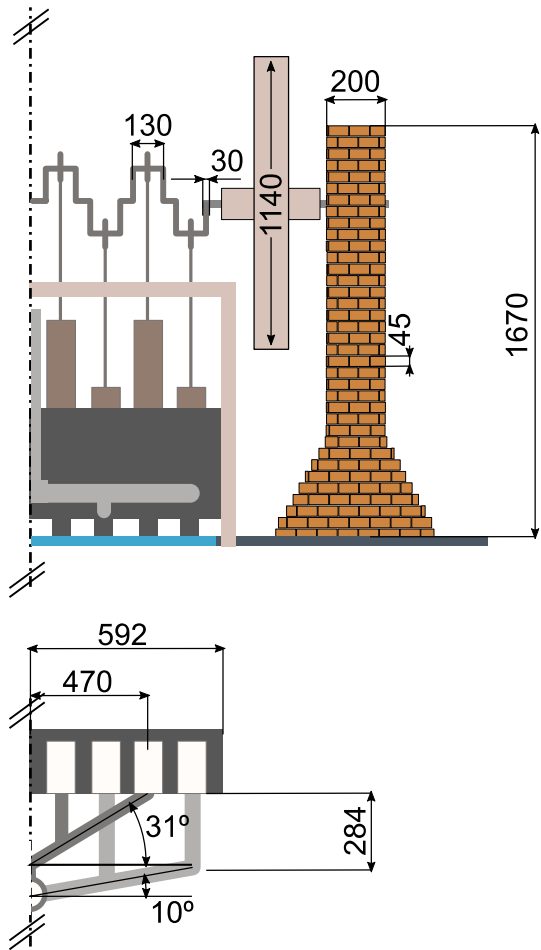
One of the main issues in obtaining a detailed design of an ancient device is dealing with and studying the current information and archeological remains. The starting point is a drawing of Fray Andrés de San Miguel [Fig. 1 shows a scheme recreated considering reference (San & Macías, 2007)]. According to Fray Andrés de San Miguel, who was present at the drainage work in Mexico City during the viceroyalty, the hydraulic pump understudy was used to drain water in Mexico City.

The illustration reproduced in Fig. 1 provided the information to identify the bill of materials and the main dimensions of the system elements. It stands to reason considering that the parts were drawn to preserve the relation among component sizes. Besides, the bricks corresponding to the structure that supports the ends of the crankshaft are the reference used to scale parts dimensions. From a specific bibliography, the bricks used for purposes similar to that of the machine were about 45 mm thick (Cristini, 2008).

Fray Andrés de San Miguel focused on the pump wit, but he did not care about how to power the system, and it is only known that it was blood-actuated. It is operated in the same way as the suction machine reproduced in "The Twenty-One Books," book 13, page 425, Figure 272 (García-Diego et al., 1996). This book, a technical manual key to understanding XVI century Spanish engineering, provides drawings and detailed explanations to understand the operation of different mechanisms (Iglesias Gómez, 2008). It also helps in selecting materials and components according to the application. For this reason, this book's assistance is critical to reproducing systems of that time.

Regarding the suction solution, this work assumed a Ctesibius piston pump with a check valve, considered a usual design in the renaissance (Moon, 2007).

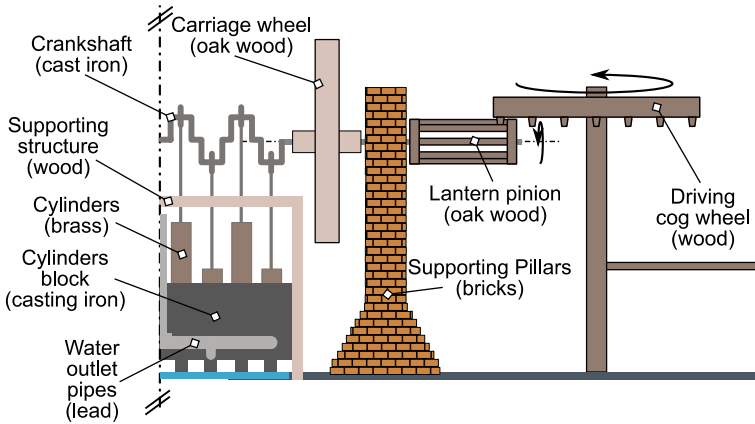
**Fig. 1** Main dimensions of the hydraulic machine under study used for draining water. Scheme elaborated considering reference (San & Macías, 2007)



Due to the enormous power requirement given its dimensions and the fact that it consists of 8 cylinders, most likely, the pump was animal-run by at least two donkeys which fit well with the symmetrical nature of the system. The system was able to raise water up to 32 feet ( $h=9.75$  m); thus, it required a pressure  $\Delta P \sim \rho \cdot g \cdot h = 95,263$  Pa close to the atmospheric one. The machine was devoted to extracting flow rather than gaining height itself.

It is needed an estimation of the animal power  $\dot{W}_{Animal}$ , an estimation of the gear performance  $\eta_{Gear}$  as well as the input–output pressure difference  $\Delta P$ , flow rate of water  $Q$ , and the performance of the pump system  $\eta_{Pump}$  to size the lantern gears that run the pump through the crankshaft and to figure of flow rate,

The power provided by the two donkeys  $\dot{W}_{Animal}$  depends on their average speed  $v$  when moving a specific load  $F$ ; both data were obtained from specific bibliography [ $v \sim 2$  km/h for  $F = 1960$  N (Chirgwin et al., 2000)]. There are no experimental studies about the performance of lantern transmission systems. This type of solution was made of wood, with a high coefficient of friction and without good geometric tolerances, which translates into mechanical losses due to sliding and impact. Based on the fact that an average current gear has an efficiency of around 80%, a conservative estimate would



**Fig. 2** Schematic reproduction of the hydraulic machine under study elaborated considering (San & Macías, 2007) for the pump system and (García-Diego et al., 1996) for the transmission one

be to consider efficiency of 0.5 given the energy losses in it. The crankshaft received this power, taking into account a  $\eta_{\text{Gear}} = 0.5$ :  $\dot{W}_{\text{Crank shaft}} = \dot{W}_{\text{Animal}} \cdot \eta_{\text{Gear}} = 2 \cdot v \cdot F \cdot \eta_{\text{Gear}}$ . On the other hand, the power needed to suction water is:  $\dot{W}_{\text{Pump}} = \Delta P \cdot Q / \eta_{\text{Pump}}$ .

The above equations help to estimate the pump flow  $Q = 24,615$  l/h. This value could not be obtained manually in any way. We considered the following hypothesis for computing the previous value:  $\eta_{\text{Pump}} = 0.6$ ,  $\Delta P \sim 95,263$  Pa,  $h = 9.75$  m.

Once known  $Q$ , it is possible to estimate the dimension of the gear lantern transmission. The lantern rotational speed  $N_{\text{Lantern}}$  is equivalent to the crankshaft one  $N_{\text{Crankshaft}}$  with can be computed as the relation between  $Q$  and the hydraulic pump volume  $V = 0.0245$  m<sup>3</sup> (computed taking into account the dimensions of Fig. 1):  $N_{\text{Lantern}} = N_{\text{Crankshaft}} = 60 \cdot Q / V = 11.1$  rpm.

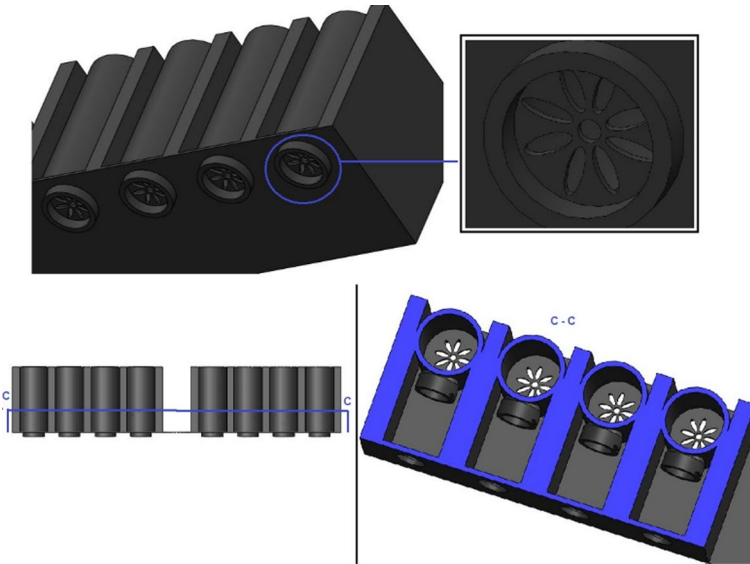
On the other hand, the driving wheel (cog wheel) rotational speed  $N_{\text{Cog}}$  depends on the donkeys' speed  $v$  and the radius of their circular movement, that it is assumed  $R = 1.5$  m:  $N_{\text{Cog}} = v / R = 5.3$  rpm.

The ratio of lantern wheel angular speed to cog angular speed  $r$  can be used to size the number of pins (teeth)  $Z$  and diameter  $D$  of the transmission components:  $r = \frac{N_{\text{Lantern}}}{N_{\text{Cog}}} = \frac{Z_{\text{Cog}}}{Z_{\text{Lantern}}} = \frac{D_{\text{Cog}}}{D_{\text{Lantern}}} = 2.09$ , for  $Z_{\text{Lantern}} = 9$  pins (according to Fig. 2) and considering  $D_{\text{Lantern}} = 370$  mm, the cog wheel has  $D_{\text{Cog}} = r \cdot D_{\text{Lantern}} \sim 775$  mm and need a number of pins  $Z_{\text{Cog}} = r \cdot Z_{\text{Lantern}} \sim 19$  pins.

### 3.2 Modelled Hydraulic Pump

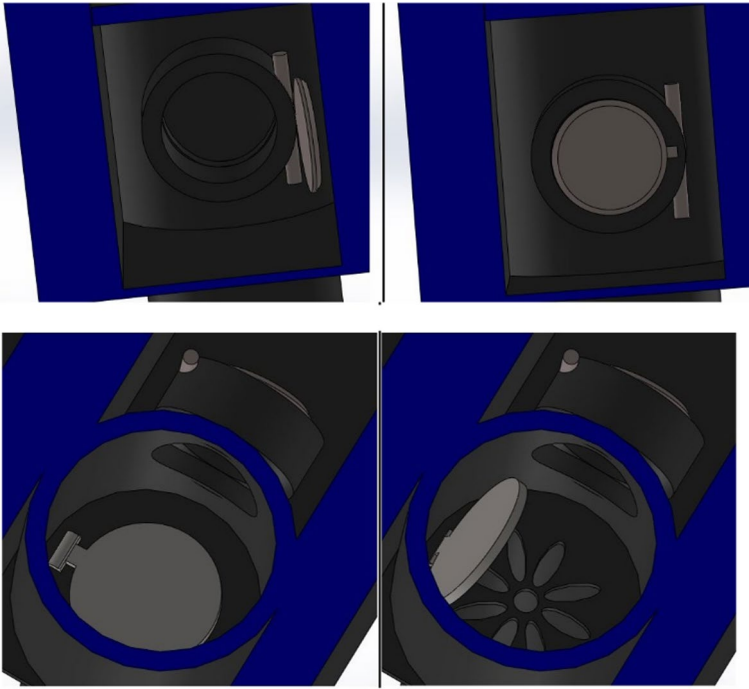
It is possible to figure out the whole hydraulic system taking into account the information collected and estimated in the previous Sect. 2.2. Figure 2 shows a scheme that reproduces the mechanism and identifies components and materials that, according to that time, most likely could be used.

The hydraulic pump consists of:



**Fig. 3** Detail of the cylinders' block modeled in a CAD software

- *Two supporting pillars* Pillars are made of brick by molding and firing ceramics, which had to be installed on a flat surface. A hole was made in their upper part at the height of the crankshaft to house it before connecting it with the transmission mechanism.
- *Two carriage-type wheels* Made of oak boards, they served as flywheels and for manual movement when maintenance was required.
- *Structure for the cylinders' block* Supported the weight of the cylinders' block, protected the connecting rods, and accommodated the machine to the soil to drain.
- *A very long crankshaft* It mapped the circular movement of the lantern gear into an alternative one and likely was made of cast iron.
- *Eight connecting rods* They were the mechanical link between the crankshaft and the cylinders. They were bent around the crankshaft so that it was permanently attached.
- *Eight cylinders contained in the same block.* The alternative cylinders' movement produced the suction pressure needed. In addition, lost-wax casting was used to produce bronze cylinders with good corrosion resistance.
- *Cylinders' block* (Figs. 3 and 4). Made of cast iron, it had holes beneath. Two valves are needed: in the base of the expulsion chamber and between this chamber and the expulsion tubes. When the cylinder goes up, it opens the valve in the chamber based, closes the expulsion one, and then water fills the chamber. When the cylinder goes down, it closes the valve in the chamber base and opens the expulsion valve propelling the water into the expulsion pipes.
- *A system of conduits for evacuating water and a set of water outlet pipes* (Fig. 5). A system of pipes comes out of the cylinders' block. It expelled the flow of water driven by the cylinders to the outside. For the operation to be possible, two tubes must go below an intermediate tube since it is the only possible geometric solution for this element to fulfill its function. These tubes are made of lead, the material used at the time for the pipes. Due to its malleability and its ambient recrystallization temperature, this



**Fig. 4** Detail of the cylinders' block valves modeled in a CAD software

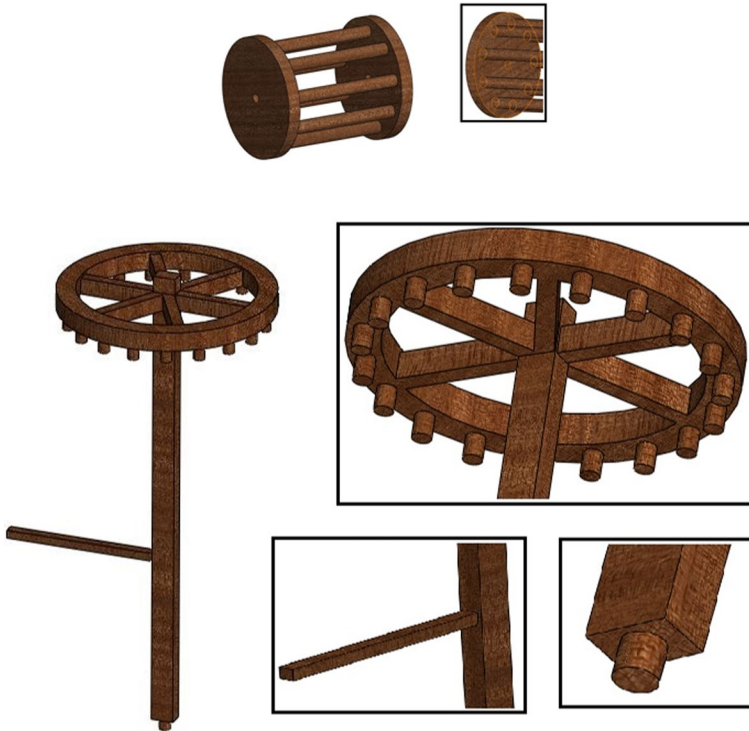
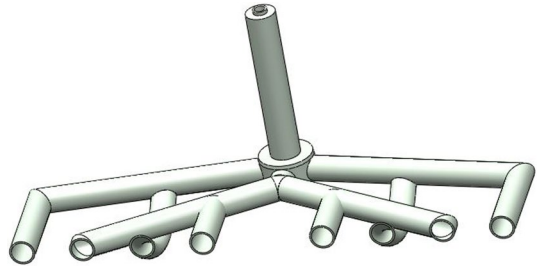
material is perfect for giving the pipes the desired geometry. Any element can be connected to its output to redirect the outgoing flow as desired.

- *Transmission system* It is assumed to be an animal-run lantern transmission mechanism (Fig. 6). The lantern pinion was made of 9 oak wood solid bars inserted into a circular base, also made of oak wood, which has the corresponding holes. The driving cog wheel was composed of 19 round, two-carved oak wood attached to a square wooden pillar through crossbars. The pillar has the structural function of supporting the upper gear wheel and allowing it to rotate, thanks to its base having a cylindrical tip that allows it to rotate around its axis. This cylindrical tip must be placed on hard material such as polished rock with a cylindrical hole or a metal hole that is also cylindrical to prevent the wood from tearing and not turning correctly. In addition, a wooden bar is attached to the pillar that acts as an axis to allow a donkey to hook onto this wooden bar and be able to transmit power to the pillar, jointly rotating the upper gear that will transmit the rotation to the connected lantern cage to the crankshaft.

The hydraulic device works as follows (Figs. 1 and 2):

- The movement of two donkeys runs a vertical wooden axis. The lantern mechanism transmits the axis circular movement to the crankshaft, which is mapped into an alternative movement.

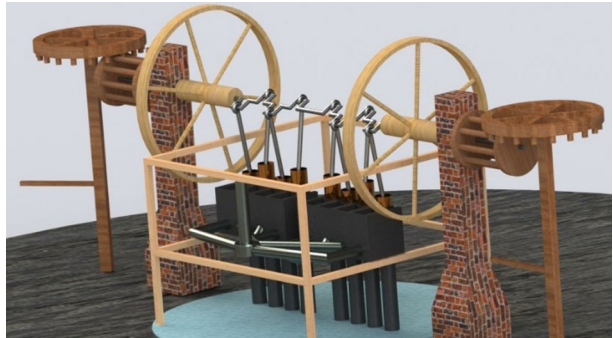
**Fig. 5** Detail of the system's pipes modeled in CAD software



**Fig. 6** Details of the transmission system modeled in CAD software

- The crankshaft moves the connecting rods, which generate a continuous reciprocating movement in the cylinders housed in the block, creating pressure differences in the cylinders, opening the suction valves, and closing the non-return valves, water entering the odd-numbered cylinders. At the same time, the pairs eject and vice versa in a continuous movement.
- The water leaves the cylinder block through a system of tubes that leads it to a vertical tube which evacuates it to the desired drainage point.

**Fig. 7** Virtual mock-up of the pump understudy



Once dimensions, materials, and system operation are known, it is possible to obtain a detailed 3D model of the system using one Computer Aided Design CAD software and simulate its movement. Figure 7 shows a rendering of the hydraulic pump CAD modeled.

#### 4 A Port Crane

This Section has the same structure as Sect. 4 but now focuses on studying a port crane. Instead of kinematic analysis, it includes a numerical study of the mechanical behavior of crane parts and shows a tangible mock-up obtained by additive manufacturing.

Callao is and was in the past the largest port in Peru. Formerly, it was an indigenous fishing village called “Piti Piti,” and its use as a pier and place of reception and departure of ships predated the formation of the city of Lima founded by Francisco Pizarro.

The first name it received was “Puerto de la Mar,” and commerce was its primary use. Proof of this is the Cabildo license to construct a warehouse on March 6, 1537, to store the merchandise produced by the port’s commercial activity (Arrús, 1904). Antonio de Herrera’s work, “Descripción de las Indias Orientales”, mentions the existence of a custom house and its large capacity and activity.

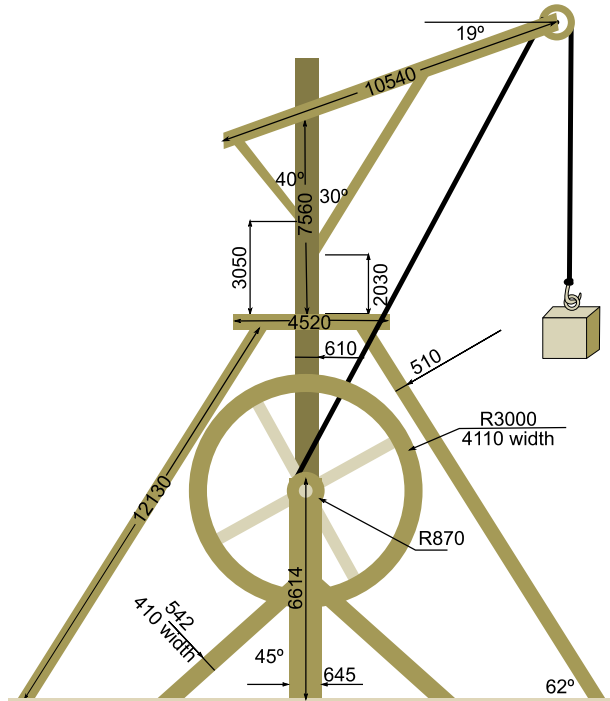
The above commercial placed the port in the spotlight of other nations, which attacked it several times during the sixteenth and seventeenth centuries. As a result, the port had to be fortified, creating the first defensive structures under the mandate of Viceroy Francisco de Toledo in 1570.

Viceroy Juan de Mendoza y Luna built a platform in 1615 with a defensive artillery system separated into three fortifications, whose shooters had a view over the entire bay. Given the danger of the continuous enemy expeditions in the South Sea, the port was walled in 1640 over the existing base. Callao became a fortified city port.

It is worth mentioning that the Callao pier was designed to avoid the cumbersome loading and unloading of the ships through rickety boats that usually overturned due to the load during the journey to the beach.

Port cranes were installed on the piers to load and unload military material, merchandise, and other heavy construction elements from boats. There is evidence of several testimonies of the first cranes installed: “port cranes were placed to unload and load merchandise. They were rotating and moved by men who stepped on large wheels, and sometimes they also had multiplications based on pulleys and hoists... As a safety measure, they used ratchets” (López-Ayala, 1985).

**Fig. 8** Scheme of crane redrawn considering “The twenty-one books: book 18”, Figure 378, page 539 in reference (García-Diego et al., 1996), and estimation of main dimensions



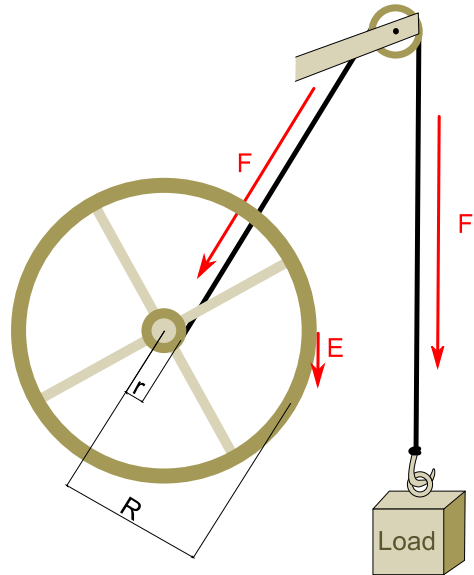
Port crane design would be based on a technical manual such as “The twenty-one books” (García-Diego et al., 1996) already mentioned in the previous Sections. This book describes a crane to lift loads, which could turn on itself and had a treadwheel. It meets all the characteristics described in the testimonials and has adequate dimensions for port use, given its simplicity and the mechanical advantage it undoubtedly provides. Therefore, the builders of the system understudy could use the schemes portrayed in García-Diego et al. (1996) to manufacture the crane. Years after its implementation, the crane was changed for improved solutions, which appeared in the “Album de construcción naval del Marqués de la Victoria” (1995).

#### 4.1 Reverse Engineering: Port Crane Reconstruction

Callao port crane, installed around the year 1707, according to the testimonies, could be based on the lifting devices described in “The Twenty-one Books,” which was the basis of the technique that probably traveled to the new world. In this book, there is a scheme of a construction crane (Fig. 8), which could be used as a port crane by extending its size and reinforcing the structure for permanent use.

The port crane consisted of a treadwheel, treadwheel support structure, pillar with a coupled pulley, pillar structure for rotation, support the weight of the people who rotate it, and finally stabilize the column to avoid buckling and unwanted horizontal displacements that would cause instability. Pillars are buried in a compacted land as the foundations of the houses of that time.

**Fig. 9** Forces scheme for the crane system



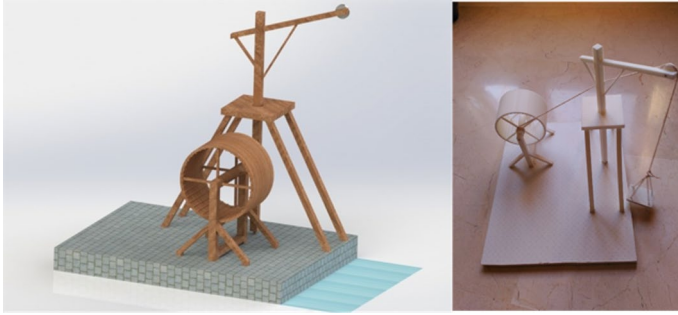
The starting point to dimension the crane elements is the definition of the treadwheel size. It should be large enough that a man can walk comfortably inside it. Once this wheel is defined, the rest of the crane elements (Fig. 8) can be proportionally dimensioned and drawn using CAD software. Considering an average man height of 1.70 m, it stands to reason to take a wheel radius of 3 m, which leaves more than 1 m between the wheel axis and the worker's heads.

It is necessary to establish the number of men needed to run the crane to analyze how it works. An energy balance provides the equations to estimate this number of workers. Taking into account the scheme portrayed in Fig. 9, the torque provided by  $n$  men that push the radius  $R$  wheel with a force  $E$  is equal to the torque transmitted to the radius  $r$  drum that winds the rope connected to the load  $F$ :  $n \cdot R \cdot E = r \cdot F$ .

Regarding the maximum weight to lift for this crane, since it was installed a few years after 1700, the heaviest constructive or military element composed of a single piece would be a 24-pound cannon, used by the Spanish navy to defend fortifications from XVI to XIX century. Its weight was  $F=2500$  kg in total, of which almost 500 kg were part of the gun carriage.

Considering that an average man weighs  $E \sim 70$  kg and his maximum step is  $R=2.7$  m inside the wheel, according to Eq. (6), the number of workers needed to lift the maximum load is  $n=6$ . Therefore, a width of 3.5 m would be enough to accommodate the 6 people inside the wheel.

It is interesting to calculate the mechanical advantage produced by the system or the factor that multiplies the force provided to overcome the resistance. Known  $r$  and  $R$  values:  $F = \frac{R}{r} \cdot E \rightarrow F = 6.207 \cdot E$ . This equation shows that it is necessary to provide 6.2 times less force than the weight to lift.



**Fig. 10** Virtual and physical mockup of the port crane studied

## 4.2 Port crane Model and Structural Analysis

Once dimensions and components are determined, it is possible to model the system using CAD software. The movement of crane components using CAD representation or a mockup, which can be obtained by 3D printing, helps to understand how to work the device. The CAD model also allows further investigations such as fundamental structural analysis using finite elements.

Considering the virtual model and the mockup (Fig. 10), the following steps summarized how the crane worked:

- Men walk inside the treadwheel made of wood and power its rotation by producing a thrust torque.
- The wheel's rotation wraps the crane rope in the drum attached to its axis. This rotation tightens the rope raising the load connected to it.
- The vertical movement provided by the treadwheel combined with the rotation of the leading crane pillar allows complex movements as required in port loading–unloading activities. For example, workers can push the timbers attached to the pillar or move the load by hand to achieve the desired lateral movement.

The pillar ends in a large metal bolt supported on its base. It makes possible the rotation and, at the same time, prevents horizontal displacements. This mechanical approach, lubricated with animal or vegetable grease, gives stability against buckling, limits lateral displacements, and reduces the bending of the pillar base.

- Once the load is lifted and turned until it rests on the land side, the men are told to stop walking since the rope's tension is lost. Very thick logs were used as a ratchet if, for some reason, the wheel had to be stopped, supporting it between the internal logs of the wheel and the base log.

The following step concerns analyzing the crane structure to verify that it can withstand the stresses to which it is subjected in operating conditions.

It is important to note that all the crane elements are mahogany wooden since it is a large tree (up to 70 m tall and 3 m diameter) to obtain the necessary pieces. In addition, its wood is robust and is very abundant in the forests of Lima. Table 1 shows the mechanical properties used in the finite element analysis for the mahogany components.

**Table 1** Mechanical properties considered for mahogany wood

|                       |                       |
|-----------------------|-----------------------|
| Density               | 560 kg/m <sup>3</sup> |
| Bend strength         | 83.3 MPa              |
| Compression strength  | 45.1 MPa              |
| Modulus of elasticity | 8.8 GPa               |

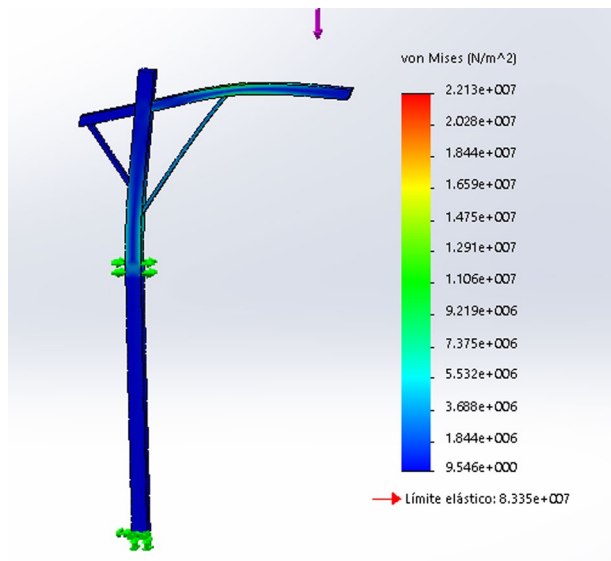
#### 4.2.1 Finite Element Analysis of the Pillar (Fig. 11)

The pillar rotates on itself and is connected to the load  $F=2500$  kg through a pulley. The joints are considered rigid since the woods are very well joined. Note that the pillar base structure prevents pillar displacements, reducing the stress within the pillar. This boundary condition is modeled as vertical sliding. After conducting a static analysis by finite elements in the software Solidworks®, the pillar that supports the load shows that it fully complies with the Ultimate Limit State for resistance. The maximum tension is 22.13 MPa, 26.55% of the material (83.3 MPa). So its service condition is safe and it possible to lift heavier loads with more than 6 workers. It is worth mentioning that the timber on the left has no structural function, so it is confirmed that it was used to rotate the crane.

#### 4.2.2 Finite Element Analysis of the Pillar Base (Fig. 12)

The pillar supports are semi-buried and completely fixed to it. A force of 6867 N is applied on the upper face, the equivalent of having ten people weighing 70 kg simultaneously on the platform, an exaggerated figure which serves to check the structure for resistance with more security.

As shown in Fig. 12, the base does not reach even 1 MPa, and the elastic limit is 83.35 MPa since its supports are very robust, and there are four, so ten people for it does

**Fig. 11** Von Mises stress in the crane pillar

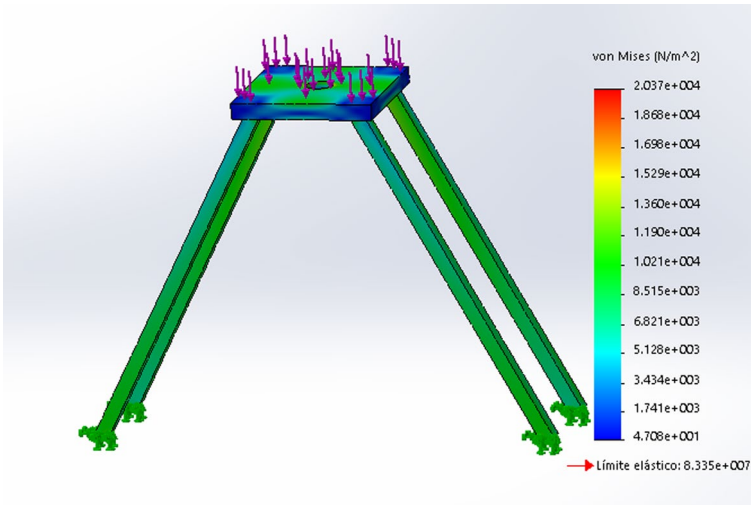


Fig. 12 Von Mises stress in the crane base structure

not suppose anything. This robustness stabilizes the pillar that goes inside and allows the crane to rotate safely.

#### 4.2.3 Finite Element Analysis of the Treadwheel Support (Fig. 13)

From the volume and density of the treadwheel, its weight can be estimated using SolidWorks® at 12,580.98 kg. A load of half the wheel's weight is applied to each hole

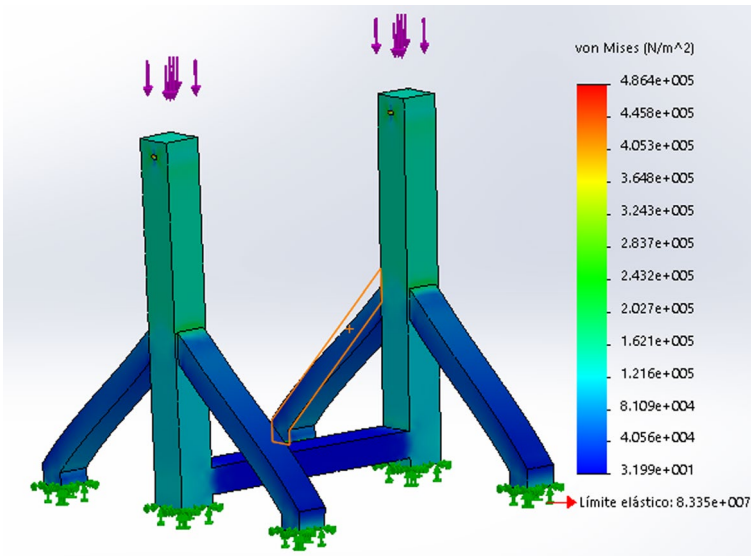


Fig. 13 Von Mises stress in the wheel support

that supports the wheel so that 6290 kg corresponds to each support, the equivalent of 61,709 N per support. On the other hand, the supports are partially buried and fixed to the ground as if cemented.

As a result of applying the conditions described above, it is observed how the maximum stress is reached in the joints with the diagonal supports, with a value of 0.4 MPa, far from the elastic limit, since this structure is oversized like the whole assembly in general with woods of great section and resistance.

It is observed that the crossbar inserted in the middle does not fulfill a structural function since the supports are embedded. Indeed, it likely was designed this way to compensate for possible movements of the supports due to the terrain, thus maintaining the structure's integrity with greater security against possible imposed displacements.

## 5 Conclusions

Technical solutions developed in Europe were critical for the development of the American colonies from the XVI to the XVIII century, as this work highlights through a reverse engineering analysis of two mechanical wits helped by CAD tools.

This work relives through virtual prototypes and scaled prototypes some mechanical wits used in the new world Spanish settlements from XVI to XVIII centuries. Specifically, this study focuses on a hydraulic pump used to drain water in the valley of Ciudad de México and a port crane installed in Callao's port (Peru). From limited historical information, the geometrical design, the engineering analysis, and numerical simulations fill the gaps in the available information helping to accomplish a detailed CAD 3D model that can be simulated or printed.

The proposed method can be reproduced following the steps described in Sect. 2. It can be applied to different devices, as shown in this work. Once come through the critical step of filling the information gaps, which is different for each mechanical device, the results of this paper prove the utility of reverse engineering to know the mechanical advantage and kinematic of the hydraulic pump and the structural stability of the port crane. Additionally, the resulting virtual CAD models and the printed scaled mockup can serve as demonstrators for museums or engineering education.

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## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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