Chapter 4
Medieval Machines and Mechanisms

In medieval times the most creative mechanical developments took place in the Islamic world. Some of those engineering and technological achievements are little-known due to the fact that, at that time, knowledge passed from master to apprentice through direct experience without being recorded in any written form. In addition, few manuscripts were actually written and only a few of them have survived through time.

The first book of the Islamic world that is known with descriptions of mechanisms was written by the three Banu Musa brothers as a "Treatise on Ingenious Devices". Around the ninth century, together they wrote over 20 works on many several subjects, but their best known work was on mechanisms.

Many of the mechanisms in the book are obtained from a translation of the works of Hero and Philo. In addition, among the 100 mechanisms that are described in the book, there are many that are related to other new machines and even they are more advanced machines than those of Hero and Philo. The Banu Musa brothers focused attention on improving ancient machines like, for example, by adding a series of siphons in Philo's oil lamp to make it more effective. At the same time they designed new machines such as fountain mechanisms, dredgers, scientific tools, agricultural machines, toys, and other automatic mechanisms whose operation is based on valve-based mechanisms, action-reaction systems, and principles of automatic control that demonstrated their creative minds. When those machines are compared to Hero or Philo's works there is less theoretical content but greater engineering ingenuity.

Each description starts with a brief summary of the purpose and motion capability of each device and then a drawing is introduced with an explanation of how it is built. The description is completed by detailed information on how it works. The major drawback is that they almost completely fail to comment on the materials, the manufacturing techniques, or the size of the machine.

The ideas that were developed for the mechanisms in the Banu Musa brothers' book were adopted by later Arab engineers, who took them as a starting point for making the first water clocks. Successively, they transmitted this culture to Spain where the Arabs founded Al-Andalus and from there it spread to the rest of Europe.

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In 1206, Al-Jazari listed a large number of machines in his book, entitled a "Treatise on the Knowledge of Mechanisms". While the explanations and the drawings are even more detailed than in the Banu Musa brothers' book, as Al-Jazari himself remarks, he seeks wider-ranging development with clearer explanations of the mechanisms and their drawings.

Al-Jazari was the most outstanding mechanical engineer of his time. This is also proved by the subsequent influence he had, and not just in the Islamic world. Many of the machines, mechanisms, or techniques that first appeared in Al-Jazari's treatise later became a part of European mechanical engineering. Some of his design contributions were on double action pumps with suction pipes, the precise calibration of holes, procedures for laminating wood to reduce wearpage, static wheel balancing, and use of paper models for design testing.

Al-Jazari divided his designs into two branches according to their technology, namely "quality" technology and "utilitarian" technology. The "quality" technology referred to machines or instruments that were designed for use by aristocrats or for scientific use. Those machines were made with strict rigour and impeccable care, even for their aesthetic appearance. Clocks and measuring devices were included among these objects. "Utilitarian" technology included machines that served for manufacturing and for workers' economy and were technically much simpler than the "quality" machines, such as mills, water-raising devices or textile machinery.

Although the Banu Musa brothers's and Al-Jazari's books are most outstanding in clocks and automatons, many other books from the Islamic world contain descriptions of former machine collections, like "The Book on the Making of Clocks and their Use" by Al-Saati Al-Khurasani (1203) and "The Book of Secrets about the Results of Thoughts" by Al-Muradi (eleventh century).

While these devices were developed in the Arab world, it was Villard de Honnecourt of France who is considered to be a forerunner of the Renaissance. This architect travelled throughout France in the first half of the thirteenth century and recorded details of building techniques and mechanical devices in his notebooks. At that time, an architect can be understood to be a combination of artist and engineer who conceives and designs a building as a whole with all its details and supervises the construction work, including the machines for it.

In the western world, technology and machines were only important within very select communities and therefore they did not require dissemination or any real technical awareness. Thus, machines and mechanisms were developed by applying past traditions and trying new solutions for specific needs. However, an intellectual approach predominated that gave no importance to technology or machines.

On Raising Water

During the seventh to the fifteenth centuries, the Muslim population was concentrated along river valleys and depended on irrigation for agriculture. The need to use river waters stimulated the invention of several water-raising devices.

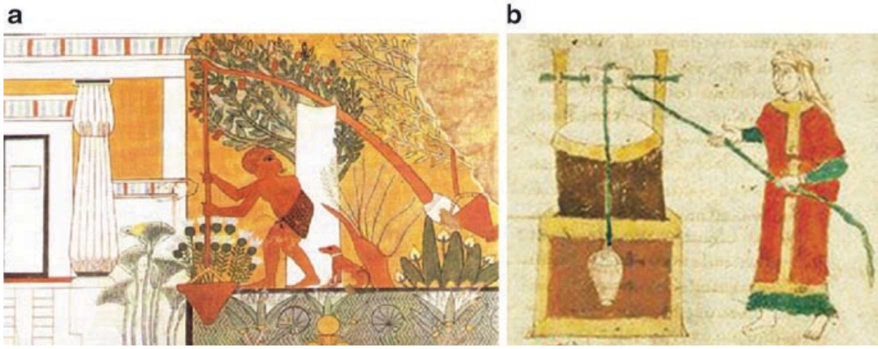

Fig. 4.1 Mechanisms for water raising: (**a**) Illustrations showing the use of the shaduf from the era of Ramses II; (**b**) Illustration from the encyclopaedia of Hrabanus Maurus, "De Rerum Naturis" [78]

The Islamic illustrations of the period make reference to some simple instruments, like shaduf, noria, and the waterwheel. Figure 4.1a is part of a painting from the tomb of Ipuy in Deir-el-Medina and dates from the era of Ramses II, and shows the use of a shaduf as a human-powered tool that was known in China, Egypt, and Syria for more than 4,000 years (Chapters 1 and 2). It consists of a rod with a counterweight that lifts a water container attached to it by an upright pole or rope. The mechanism's simplicity makes it possible to use local materials.

Since it is easier for a man to exert a downward vertical action, the counterweight is used to operate the lifting of the water weight and the human operator pushes the shaduf rod down. Once the water has been raised, it can be used to fill irrigation channels or reservoirs, or even can be channeled to higher ground by using several shadoofs in series.

Another very simple water-raising device can be noted in the drawing in Figure 4.1b, where water raising is achieved by a rope and pulley. The illustration is taken from the encyclopedia "De Rerum Naturis" from circa 1022 by Hrabanus Maurus, preserved in the Abbey of Montecassino. In this case, it can be noted that raising water requires greater human effort since there is no counterweight as in the shaduf.

As regarding the waterwheel and the noria, the main difference can be identified in the source of the driving force, which is often obtained by animals in the noria, while with the waterwheel, it is the force of the water flow that turns the wheel to transport the water. In general, a noria is used for lifting water from wells, while the waterwheel can be used in fast-flowing rivers.

If Fig. 4.2 is compared with Fig. 2.8, the difference can be well appreciated. With the waterwheel, we can see that the wheel, which is powered by water flow, there is no need for manual driven power. However, in the noria, a beam is connected to the wheel shaft that generates the movement supplied by an animal through the required force.

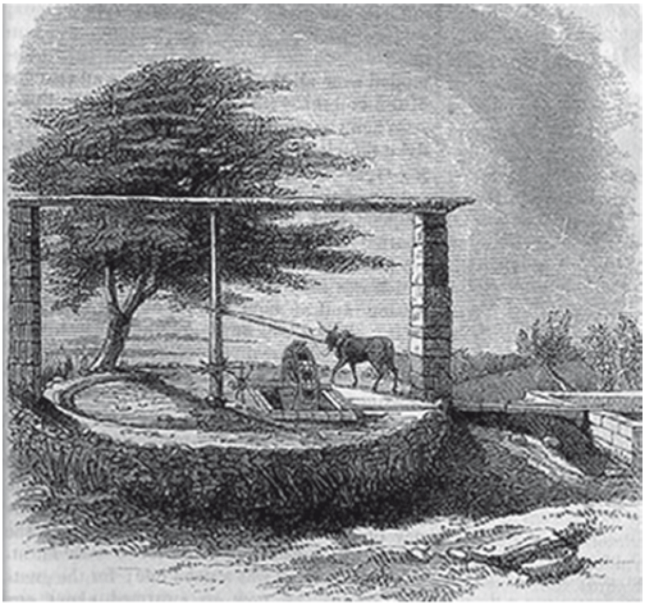

Fig. 4.2 Illustration of a horse-driven waterwheel

The shaduf, the noria, and the water wheel do not represent any significant innovations with respect to the devices pre-existing in China (Chapter 2), although, in the Arab world, they were built more perfectly, maybe due to a greater need for efficiency in the use of water resources.

The next illustrations from the treatise by Al-Jazari provide technical solutions of a greater constructional complexity that reveal a greater capacity than in previous cultures for ingenuity relating to the use of hydraulic machinery.

For some erudite current scholars of this period of history, the author's aesthetic representation and beautiful, careful presentation of some of his designs are due to the fact that those machines are Utopian and they never existed at that time. However, other scholars consider their aesthetic design features to be of a practical nature, derived from the need to improve the efficiency of water-raising methods by conceiving mechanisms for this purpose. Regardless of the foregoing, their designs have the added significance of incorporating important techniques and components for developing machine technology.

Among other machines, Al-Jazari presents a spectacular mechanism in Fig. 4.3 with two continuous operation sub-systems that are operated by animal power. The first sub-system is represented in the lower part of the illustration. A water tank has a hole through which the water falls in a way that causes a bucket-carrying wheel to rotate together with a horizontal shaft. This horizontal shaft is fitted with a gear-wheel that engages another horizontal wheel that transmits the motion to an upright vertical shaft.

Fig. 4.3 Al-Jazari's water raising device [9]

The second sub-system has two driving forces, namely one is obtained using an animal that is tied to the shaft and a latter one comes from the movement of the bottom sub-system. Both forces rotate the upper vertical gearwheel that operates a second horizontal shaft to raise water from the tank to an aqueduct by means of containers that are connected to ropes rotating around a pulley.

Al-Jazari also shows designs, that were based on tilting movements as an innovation for water raising procedures, several centuries before Juanelo, who also built a machine with tilting buckets to supply Toledo with water.

The machine in Fig. 4.4 shows the use of lantern-type gear wheels. It is composed of two large vertical columns that are placed in a tank to house two cross-shafts. The lower shaft incorporates a scoop and a lantern. The upper shaft has two gear wheels. One is made with teeth on a quarter of its perimeter only, and it engages the lantern, while the second wheel receives the movement from an animal-powered horizontal gearwheel.

When the animal moves, the partially toothed gear is rotated. During the toothed quarter turn, the lower lantern engages the wheel that rotates the lower shaft, forcing the scoop to rise. During the other three-quarter turn, the scoop falls and picks up water so that the cycle starts again when the lantern re-engages the gearwheel.

In the next figures, Al-Jazari obtains a tilting movement by using sliding crank-operated mechanisms. This is probably a more efficient solution than using partially toothed wheels, which would lead to large fluctuations in the required torque.

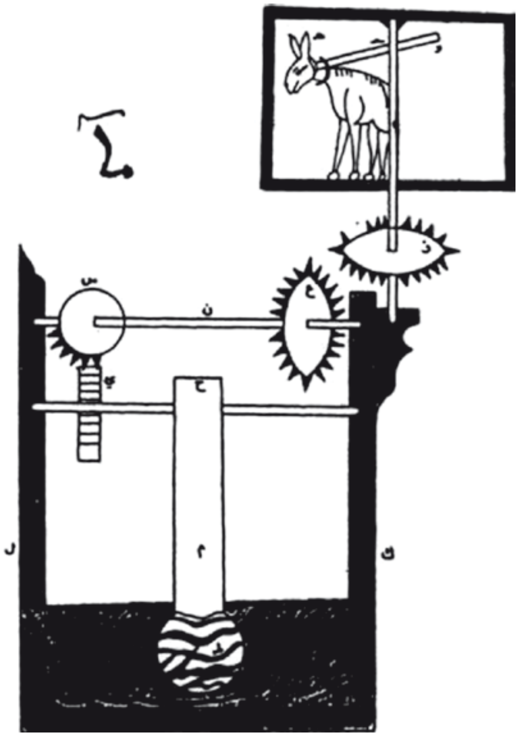

Fig. 4.4 Al-Jazari's alternating water raising device [9]

Figure 4.5 shows another water-raising device by Al-Jazari. A circular movement that is obtained using animal traction is again used to rotate a gear assembly with two wheels on perpendicular shafts. It can be noted that the horizontal shaft incorporates a crank whose free end is housed in a groove made of a scoop in the upper part and the lower part is submerged into water. The turning movement of the crank pushes the scoop to rise and then to fall in a tilting movement raising the water. How the device worked can be better understood by referring to Donald R. Hill's reconstructions in Figs. 4.6 and 4.7.

Figure 4.6 shows the scoop when submerged into water with an ascending stroke. In Fig. 4.7, the spoon is fully raised out of the water and is now ready to empty the water via a tilting channel. In the last movement, the scoop returns to the water to begin the cycle once again.

Al-Jazari mentions other water-raising devices that make use of alternating movement through crank-slider mechanisms.

In Chapter 3, it was discussed how the suction-impulsion pump was already used in the Greco-Roman world. Figure 3.18 would suggest manual operation for this type of water pumping as well as the fact that it may have been used in mining galleries.

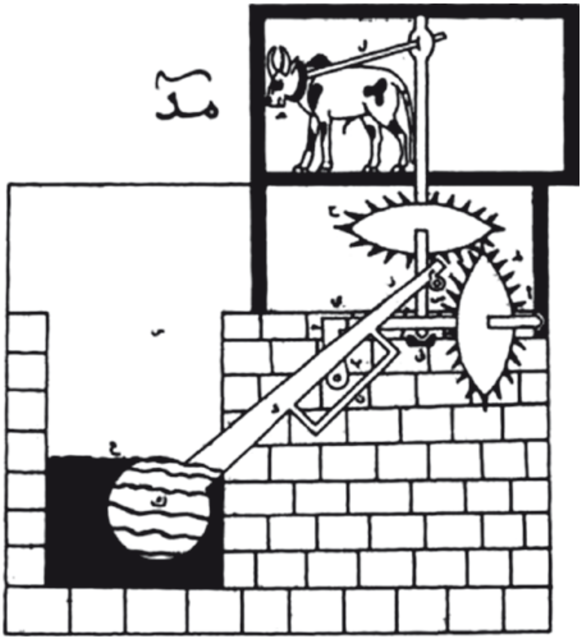

Fig. 4.5 Al-Jazari's water raising device [9]

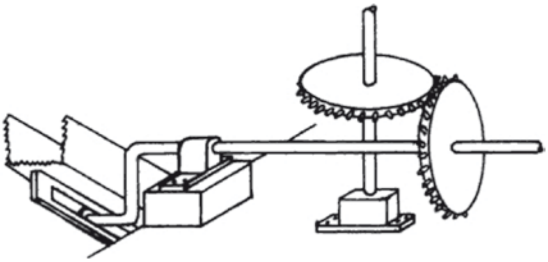

Fig. 4.6 Detail of the device in Fig. 4.5. Donald Hill's reconstruction [9]

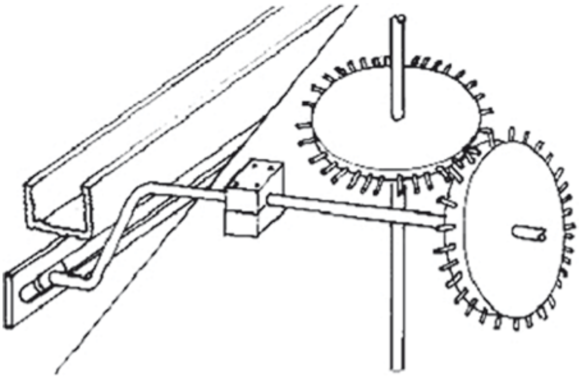

Fig. 4.7 Detail of the device in Fig. 4.5. Donald Hill's reconstruction [9]

The innovation in Al-Jazari's treatise consists in the fact that it is the water flow that is the driving force, as can be observed in the following.

An example of this is the double-effect pump in Fig. 4.8. This machine incorporated mechanisms from two previous machines, namely the paddle-wheel operating the noria and the siphon-pumping device that was described by Philo. It seems a practical device that is aimed at solving a specific problem for raising water cheaply and efficiently from deep rivers up to the surrounding fields and settlements.

Coupled with the gearwheel at the bottom, a lug can be noted that slides like a cross-piece, in the groove of a slide, whose lower end is pivoted at the bottom of the machine. Attached to both sides of the slider are connecting rods that are connected to the head of the two pistons. The copper cylinders contain pipes for suction and outflow. Those pipes connect the two cylinders and the latter operates as non-return valves. The two supply pipes come together as one in the upper part of the machine.

The water-powered paddle wheel operates a gear assembly that transmits movement to a second shaft. The rotation of the gear wheel in the second shaft produces the tilting of the slide by using the lug-slide, This moves the attached pistons from side to side with an alternating movement, so that when one cylinder is sucking, the other is emptying. This motion produces a fairly uniform out-flow through the outlet pipe.

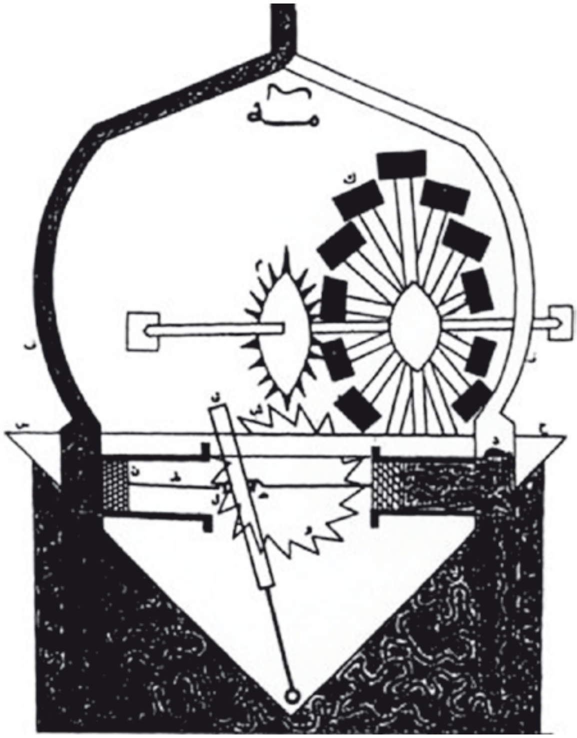

Fig. 4.8 Al-Jazari's pumping device for raising water [9]

Later, in 1551, Taqi al Din, in his book “The Sublime Methods of Spiritual Machines”, presented a more productive machine for raising water more uniformly. The machine is based on a common six-piston transmission. It is the so-called six-cylinder mono-block pump that is shown in Fig. 4.9, as an evolution of Al-Jazari’s primitive machine.

The water flow drives a transmission with six cams. Each cam governs the movement of one of the six pistons. A suitable angular bias of the cams on the shaft achieves an uncoupled movement of the pistons and a more uniform water flow in the pumping pipe.

When the water flow was insufficient, the alternating movement produced by the action of the water flow stimulated Al-Jazari to other brilliant designs. Among his designs, one of the most noteworthy solutions is the fountain in Fig. 4.10 which forms part of his “utilitarian” technology.

This fountain was fed with water from the top with a pipe that emptied into a tank on either side. The ends of the pipes were open and, near to each end, there

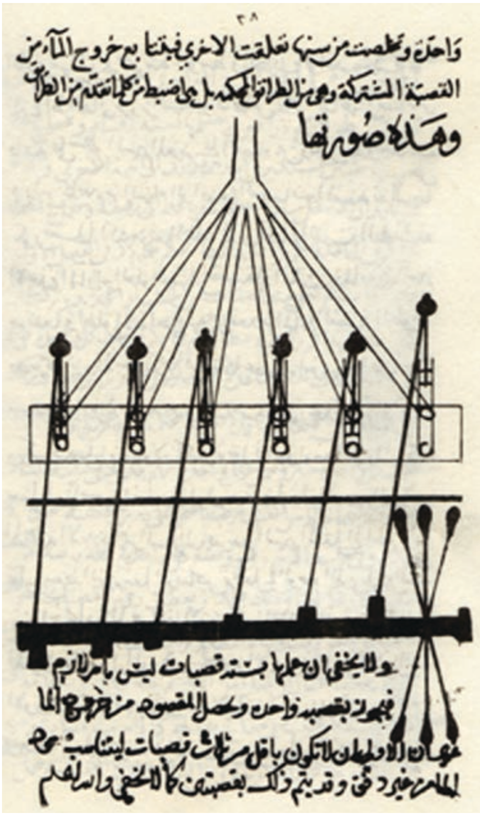

Fig. 4.9 Taqi al Din’s water raising machine [7]

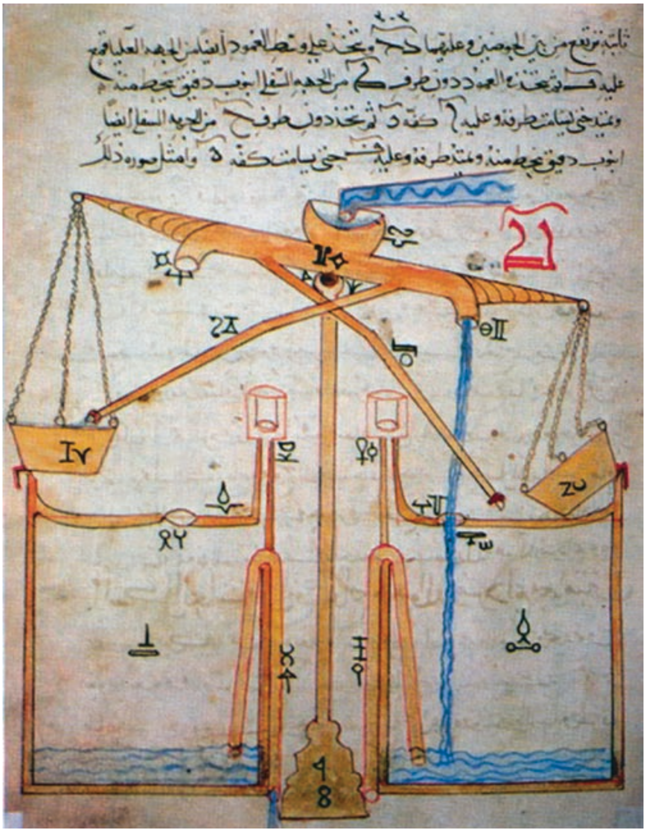

Fig. 4.10 Al-Jazari's fountain [9]

was a thin pipe that emptied on the opposite side into a bucket suspended from the top part. The whole of this machine was pivoted and could tilt from side to side.

In the configuration that is represented in the drawing, the pipe is emptying into the right-hand tank, while water is flowing gently into the left-hand bucket from one of the thin pipes. When the bucket is full, the weight of the water makes the top assembly tilt to the left and it starts to empty into the other tank through different sizes and groups of streams. The cycle is repeated while the water supply is maintained.

On Clocks and Automatons

Around 975, Al Biruni devoted himself to trigonometry, mechanics, and astronomy, and he described the so-called "Moon Box" in his book "An Elementary Treatise on the Art of Astrology".

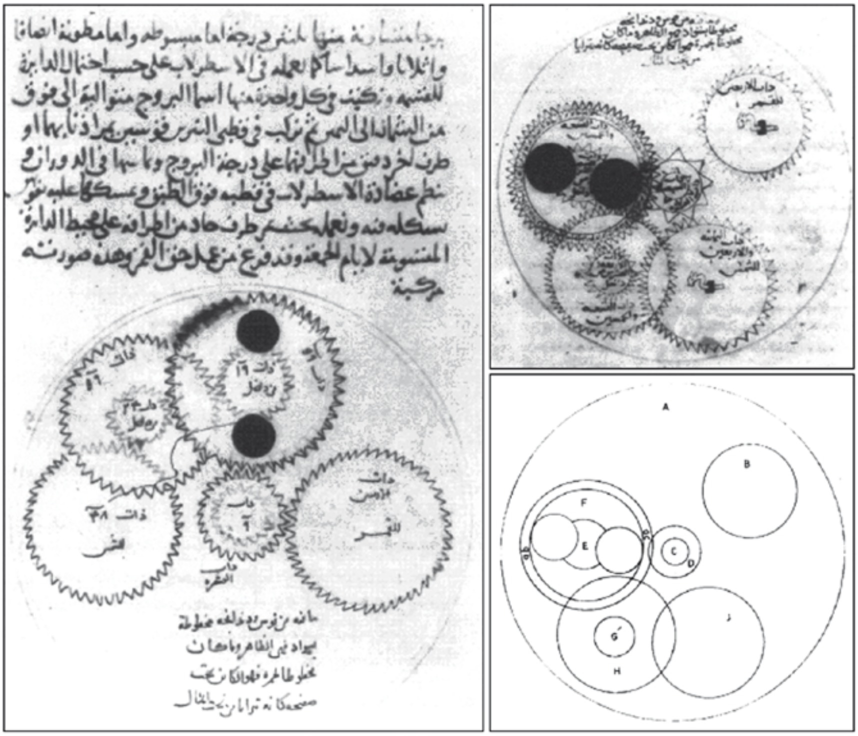

Fig. 4.11 Al-Biruni's Moon Box [4]

The purpose of the box was not only to make an approximate measurement of the phases of the moon but also to measure its position and that of the Sun. It also showed the signs of the zodiac, the days of the week, and the hours. The mechanism was based on eight interlocking gearwheels (Fig. 4.11) each of which had the exact number of teeth for its specific task.

Al Jazari combined clocks and automatons with superb precision. Figure 4.12 shows a candle clock that was designed to measure the passing of 14 equal periods of time. A uniform cross-section candle was used with a wick and a specified amount of wax. A long jacket with a perforated lid was welded to the candle support. A support plate was placed at the lower part of the candle to which a U-shaped channel was welded as divided into 14 compartments where the 14 balls were situated. A weight was positioned to continually push the candle upwards by using a rope-and-pulley system. When the flame was lit, the lid had to be frequently cleaned to ensure the flame remained constant. As the candle was gradually burned, it was slowly forced upwards by the action of the weight and the support plate. At the same time, the pulley system operated an indicator to move. After a time cycle, the first of the balls is loaded into the conduit and reaching the exit, rolls into the bird's head and comes out of its articulated beak to be recovered from a bowl.

Fig. 4.12 Al-Jazari's candle clock [9]

Figure 4.13 shows a scribe with a quilt in his hand sitting on a bucket-shaped structure. The hour is indicated by means of a horizontal ring set on the structure and divided into 217 parts, which each 15 divisions represent 1 h. The scribe marks the hour with his quilt which is at the beginning of the day in the first division.

For the rotation of the scribe, there is a mechanism inside the tank which can be noted at the side in the diagram. The scribe is connected to a shaft attached to the bottom of the tank and is moved by a pulley that is observable at the foot of the scribe.

When the tank is filled up to the required height, a hole of the right size at the bottom permits sufficient water to drain that, in 1 h, turns the scribe for the 15 divisions. The water flow produces a turning motion through a pulley where a rope is attached to a weight floating on the water. The other end of the rope is connected to a counterweight to retain the weight balance once the rotation is achieved.

When the water has been poured in, the counterweight is at its lowest point but, as the water drains, the lower weight rises and the pulley turns. Thus, the scribe

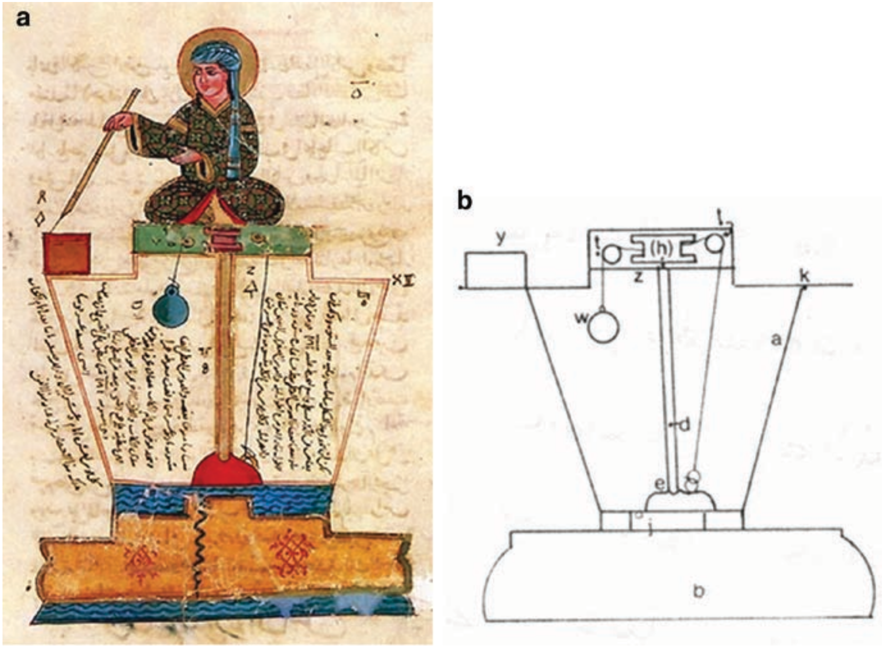

Fig. 4.13 The scribe clock automaton by Al-Jazari: (**a**) the original drawing; (**b**) a reconstruction drawing by Donald Hill [9]

turns with it while the quilt points to the hours. Once the water has completely drained, the tank needs to be filled again.

Of all Al-Jazari's clocks, one of the most famous constructions was the elephant clock that is shown in Fig. 4.14. This was used as an astronomical instrument for the exact measurement of time.

The complexity of this clock design and other similar ones required meticulous assembly. Donald R. Hill showed the mechanisms of some of these clocks in detail (like in Fig. 4.15) when he translated Al-Jazari's book into English in 1979, and made drawings to explain their working.

The bowl (a) floats on the surface of the water in a tank (n), to which it is connected by a joint with several articulations (b) that are indicated on the left. In the upper part of the clock, there is a domed castle that is supported on four columns. Inside the castle there is a ball dispenser that is not shown, from which a conduit leads to a bird head (f). The serpent tail, which in reality is a pulley, is part of a shaft that is installed on bearings. A chain (d) connects the underside of the bowl to a serpent tail, while a cable (h) is connected to the bowl and the ball dispenser by a small piston and a hole (k).

At the beginning of the time period, the empty bowl is on the surface of the water. A calibrated hole regulates the water flow, slowly sinking the bowl until the end of the period when it suddenly submerges. This causes the cable (h) to operate the ball

Fig. 4.14 Al-Jazari's elephant water clock [9]

dispenser and a ball falls from the bird beak into the serpent's mouth. The serpent's head drops and the chain (d) pulls on the bowl, which empties its contents since it is articulated at (b).

The ball drops from the serpent's mouth and strikes a small bell. When the whole movement is finished, the serpent's head returns to its initial position. The empty bowl is again horizontally floating on the surface of the water and the cycle starts again. The clock continues to work while there are balls in the dispenser.

The water flow regulator can be considered to be one of Al-Jazari's great contributions as it consisted in a perfectly calibrated hole through which the bowl gradually submerged to produce the exact flow velocity for different variations in water velocity. It was this immersion that marked the time of the hours, and this means

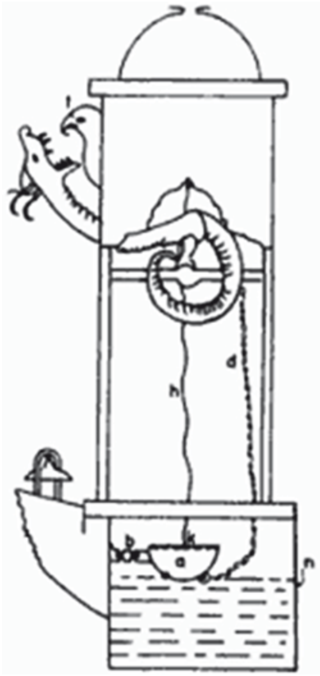

Fig. 4.15 Donald R. Hill's drawing for explaining a Al-Jazari water clock [9]

that Al-Jazari must have performed several experiments and trials before coming up with the exact size of hole to obtain a perfect hour counter.

Al-Jazari used the force of gravity as an engine to make the bowl sink and also for the dropping movement of the serpent's head when it had a ball in it.

Besides these mechanisms, he used two others, namely a return mechanism and a control mechanism. As already noted, the return mechanism is activated when the ball has dropped from the serpent's head, while a pulley makes the head return to its original position, and the submergible bowl rises to the surface, losing the water that it has picked up.

The control mechanism is located in the bowl and the control law is marked by its fall-and-rise cycle, which is maintained while there are metal balls in the dispenser (as a closed loop cycle). It can be noted that a cable and chain are attached to the bowl; the cable goes from the ball to the bowl, and it is this that releases the mechanism inside the castle and activates it when the bowl has sunk. However, the chain goes from the underside of the bowl to the serpent's tail and its task is to tilt the bowl to empty out the water.

One example of the design mechanical complexity and precision was a clock that gave information on the phases of the Moon and the position of the Sun in the signs of the zodiac. This was a measurement of time not only on an hourly and daily bases, but also on a monthly and yearly basis.

The system in Fig. 4.16 shows this complex mechanism, which has a wheel at the top that is illustrated with the 12 signs of the zodiac. Below there are two half-circumferences; the upper one marks the state of the Sun by means of a golden sphere and the bottom one marks the state of the Moon by means of a glass sphere.

The appearance of a figure at each of the 12 windows on the top row marked the passing of the hours. The row of doors beneath changed colour depending on whether the indicated hour was for day or night. At the same time, the two birds at the sides tilted forward by pushing a sphere to fall from their beaks into the goblets and by activating some cymbal sounds. In addition, at the sixth, ninth and twelfth hours, a device was pressed that activates a music band.

The clock ran on a complex system that is based on a water-flow regulator to measure the times, as shown in Fig. 4.17.

The movement was carried out by the lower guide along which a carriage moved horizontally. Consequently, this carriage moved the figures appearing in the windows of the upper frieze.

Fig. 4.16 Al-Jazari's clock [9]

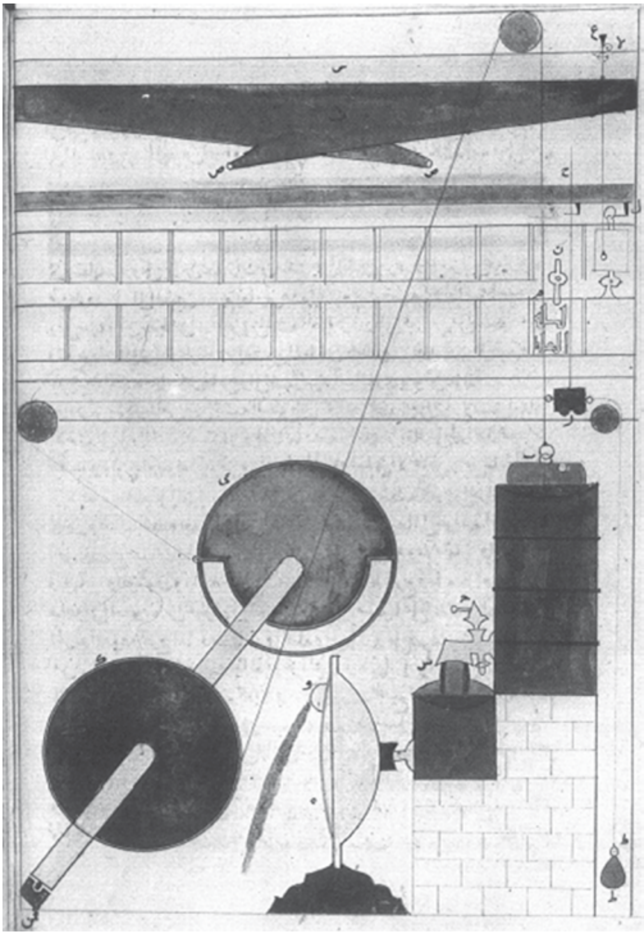

Fig. 4.17 Time marking mechanism [9]

The system was based on a water tank whose water flow was regulated by a tap and a series of pulleys and pistons which transmitted also the other movements. The water coming from the tap moves continuously down the piston, which pulled on the upper pulley and the large lower wheel. As this wheel is rotated, the shaft on which it is installed, is rotated and, consequently, the upper wheel is rotated too. The thread connecting this wheel and the carriage guide completed the movement.

The water regulating mechanism had to be perfectly calculated in order to stop the water falling after 12 h, and, consequently, the top of the shaft with the carriage that is located at the last window corresponding to the twelfth hour. When the tank was again filled, the shaft rotated in the opposite direction and the carriage returned to the first hour in order to be ready to begin the cycle again.

Fig. 4.18 Pages from Al-Jazari's book. (**a**) Drawing and explanation of an automaton. (**b**) Page of explanations [9]

Figure 4.18 shows two pages from Al-Jazari's book illustrating details that he wished to present his work as fully descriptive and detailed drawings and precise explanations.

Al-Jazari presents many more automaton mechanisms for several purposes, such as to serve wine, to dispense fruit, for washing hands or making music. These automata were used as toys or for entertaining guests.

The illustrations in Figs. 4.19 and 4.20 show some of these automata.

All these are prime examples of a refined culture that devoted a large part of its mechanical brilliance and inventiveness to producing luxury objects endowed with movement. The overwhelming superiority of Muslim trade over many centuries should not be forgotten. Their trade relations were extended to the whole of the known world, and particularly products that were directed to the upper classes of the cultures they had relationships with. Automatons, like those described above, would have been among those products.

Prior to the authors previously mentioned, in the ninth century the Banu Musa brothers wrote their "Treatise on Ingenious Devices" which had a great influence on subsequent machine design in the Muslim world. Although it can be considered a key book for the history of machines, the explanations given in it and the drawings themselves are not fully clear. This sometimes makes it difficult to interpret the illustrated machines, which have been clarified by the comments of later Arab writers.

Fig. 4.19 Al-Jazari's wine and water serving devices [9]

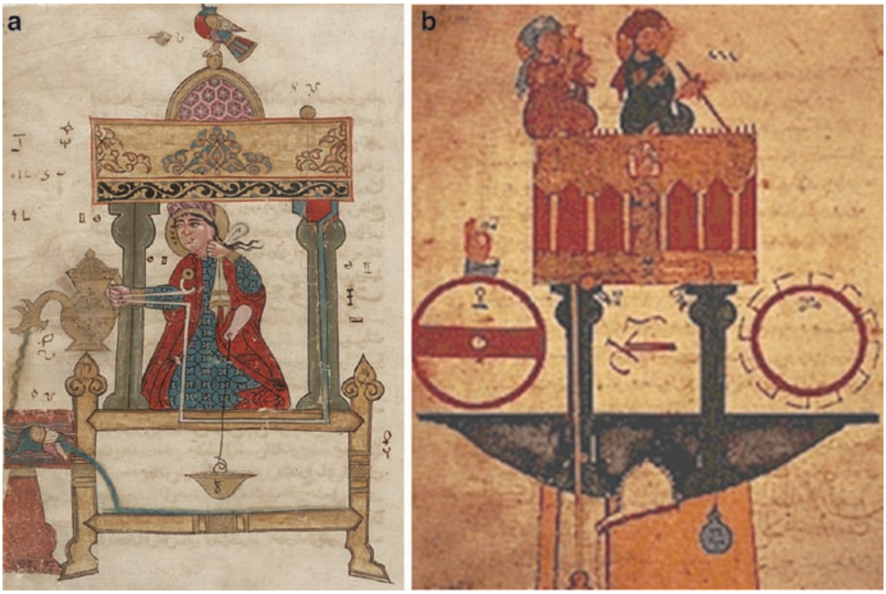

Fig. 4.20 Al-Jazari's automatons [9]

Nevertheless, in order to complete the contribution of Muslim culture, this history cannot miss to mention the Banu Musa machines. Figure 4.21a shows a lamp installed inside a hemisphere that is capable of self-adjustment by means of a rack and pinion. Figure 4.21b shows two of the Banu Musa brothers' even more advanced devices. As the devices evolved water energy was used as the driving force.

They are at least examples of how mechanical automatons were developed, from the beginning of the spread of Islam.

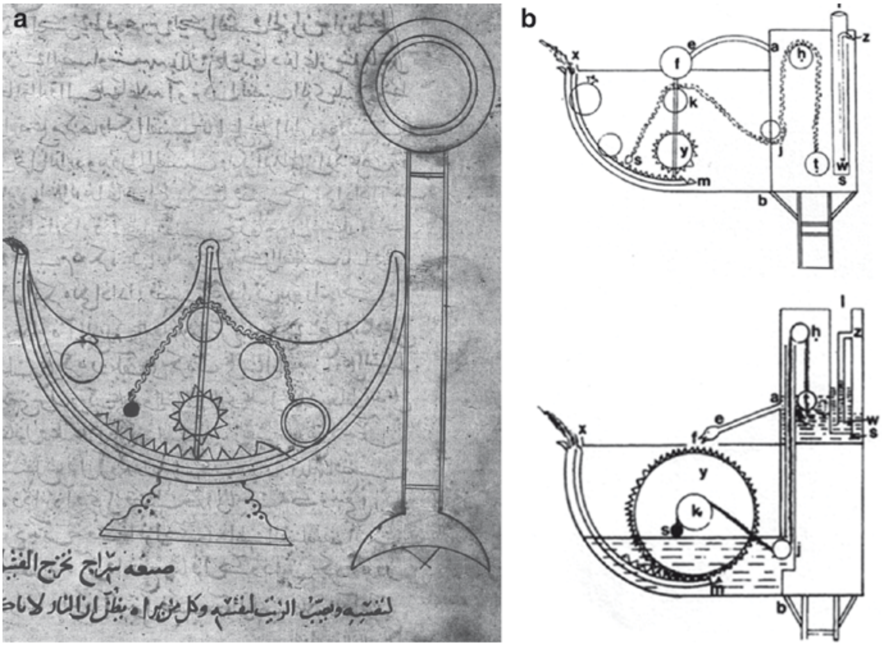

Fig. 4.21 One of the Banu Musas' lamps: (**a**) the original drawing; (**b**) Lamp diagrams for interpretation [63]

On the Transition in Europe

Progress in the Arab and Asian worlds did not appear to have reached Western Europe until the thirteenth century. However, some European inventions did exist, like the arrow launcher shown in Fig. 4.22, that is taken from a drawing by Villard de Honnecourt with a similar structure to some of the Chinese catapults in Chapter 2.

With the help of Fig. 4.23, the way the machine works can be clearly explained thanks to the interpretation through drawings by the French National Library (BNF). The first thing to surprise us is the sheer size of the device if we consider that the figures are drawn in scaled size, since Villard de Honnecourt's machine was apparently of 18 m high.

The mechanism consisted in driving the arrows forward by using the thrust of a pivoted plank. This plank was made to fall with the help of two pulley systems that were on each side on the ground and were attached to ropes also connected to the plank. The force required by the operators was not only to drop the board but also to raise the attached counterweight. Villard defines the counterweight as "an enormous basket full of two large "toesas" of earth (French unit equal to 1,949 m long, 9 ft wide and 12 ft deep, once the counterweight had been raised, the rope was cut (Fig. 4.23b) transmitting the movement of the counterweight to the arrows when the

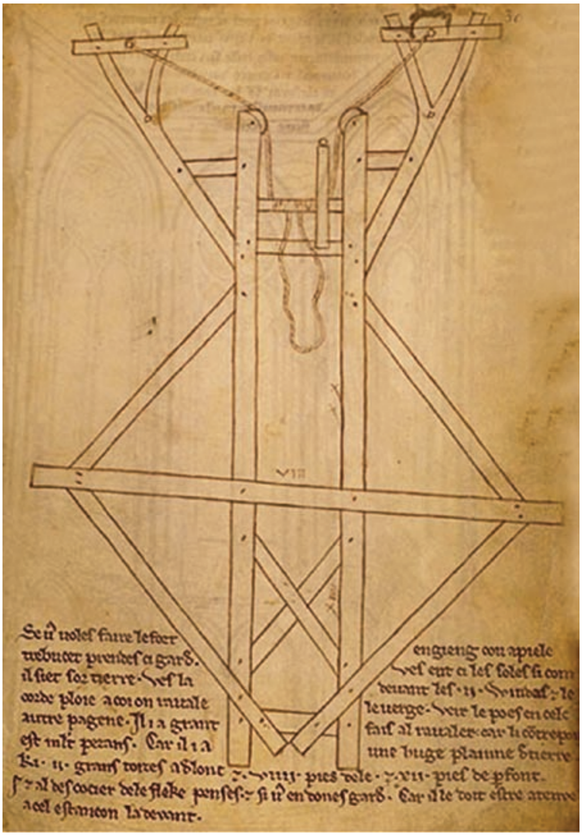

Fig. 4.22 Villard de Honnecourt's arrow launcher [64]

edge of the plank hit them. Obviously, a machine of such a size provided a large force and obtained very long shots that could have been useful for besieging cities or fortresses. The studies made by the French National Library refer to 100 kg projectiles whose energy necessary was able to destroy bridges or smash through defence walls.

The book begins with the words "Villard de Honnecourt greets you and asks that all who use the devices in this book pray for his soul and remember him. For this book shall be of great assistance in building work and in joinery machines …" One of those joinery machines is a saw for cutting piles in water, as illustrated in Fig. 4.24. Both the original figure and the one by the French National Library show the peculiarities of the mechanism.

The saw in the drawing is fixed horizontally to a frame situated above the water and it is supported on a platform, where two workers on either side of the saw, as shown in the figure to the right, move the platform by pushing it backwards and forwards.

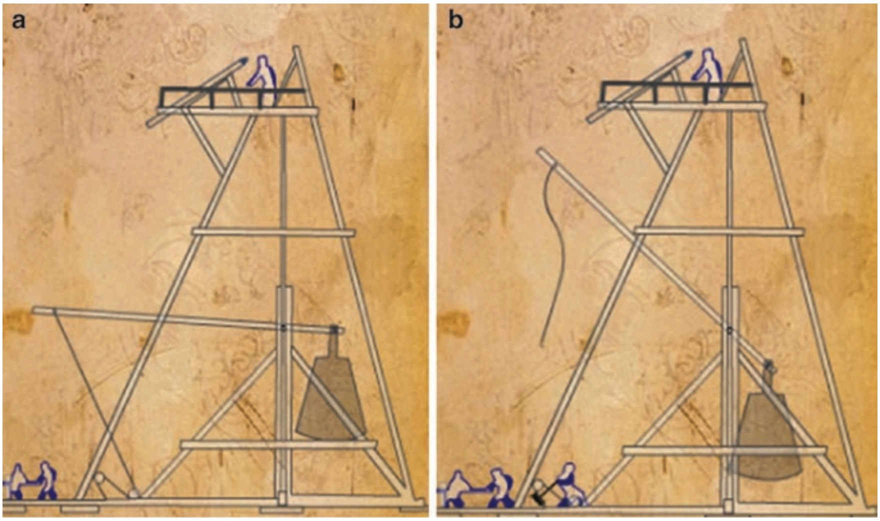

Fig. 4.23 Positions of Villard de Honnecourt's arrow launcher. (**a**) Falling. (**b**) Rising. Reconstructions by the BNF

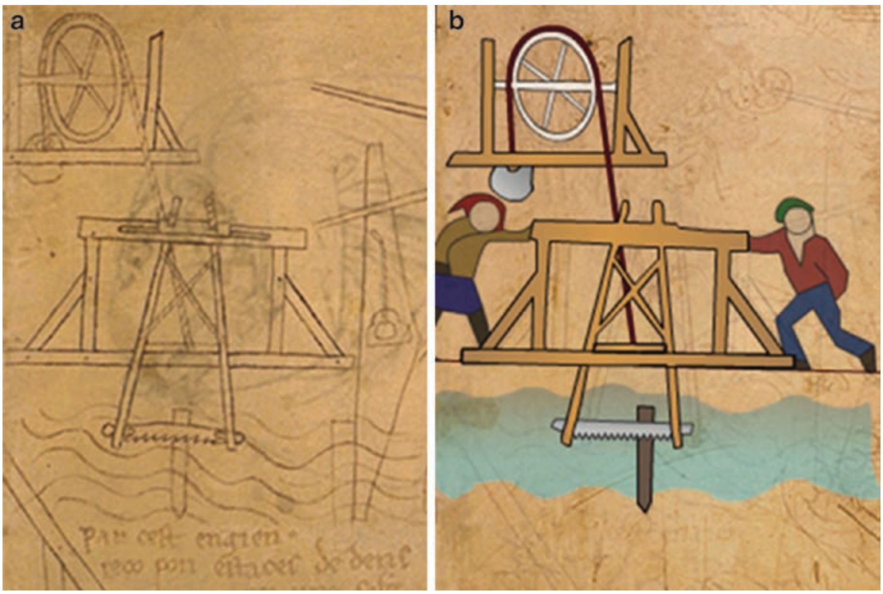

Fig. 4.24 Villard de Honnecourt's saw for cutting wood under water. (**a**) Original drawing [64]. (**b**) Reconstruction by the BNF

Villard de Honnecourt placed a wheel with a counterweight attached to the saw with a rope so that it would exert pressure on the pile to be cut and assist the movement. He also drew a plumb-line to the right.

The book also contains a water-driven saw. Honnecourt writes of this machine: “A sword is thus made that saws all by itself”. Although there is a lack of illustrated documents, everything would seem to point to the existence of hydraulic power in the West, probably for fulling mills and other uses.

Figure 4.25a is the first illustration of a hydraulic saw. It had previously been described and used but never drawn until Villard produced his notebook. If the crudeness of the actual drawing reflects the actual construction, the difference from contemporary designs from the Muslim world is highly remarkable.

In this saw, the circular motion of the waterwheel creates an alternate rising and falling movement that is capable of sawing wood, to which is added a wheel’s automatic forward movement towards the saw. The water turns the wheel by means of the schematically represented paddles and, consequently, its shaft rotates the wheel with four cams. A drag wheel is used to advance the piece of wood that is held among four supports to stop it moving from the horizontal position. The work of the cams is to drive the articulated arms at the foot of the saw.

This second movement is based on the attachment of the saw at the top to a flexible pole. When the articulated arm is leaned on, the cam forces the saw down, which bends the flexible pole and then it makes it rise again to its original position. This is an impulsive movement but it is effective, since the lower articulation was designed so that the movement does not lose its verticality.

The saw guide mechanism may be interpreted as quadrilateral where a coupler is used to guide the saw in its alternate movement. This mechanism was not to be used again until James Watt’s steam engine appeared in 1775. By observing the machine in Fig. 4.25, we can conclude that technical development took place during the Middle Ages in Europe. However, there was a limited awareness and spread of this technical culture which only reached maturity during the Renaissance.

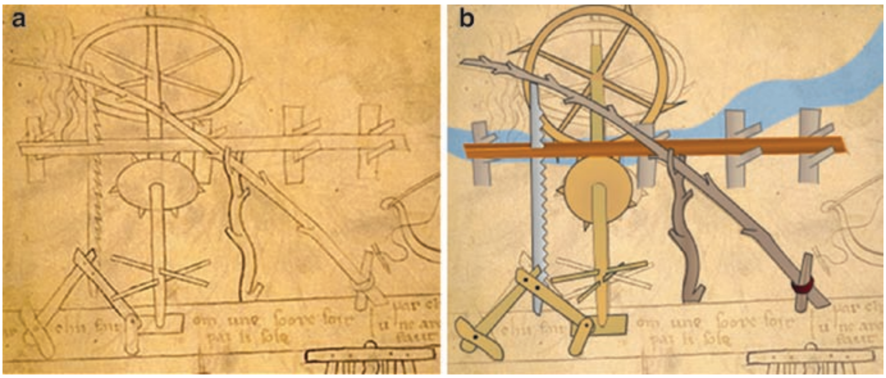

Fig. 4.25 Villard de Honnecourt’s hydraulic saw. (**a**) Original drawing [64]; (**b**) a reconstruction by the BNF

Fig. 4.26 Villard de Honnecourt's elevator [64]

Thanks to Villard de Honnecourt, we also have an illustration of an elevator as shown in Fig. 4.26.

The reconstruction in Fig. 4.27 depicts a wooden shaft where the top two-thirds have been turned, while a horizontal handle has been added to the bottom third to produce the rotary movement of the shaft. The ends of the screw are fixed, while a nut and some crossbars stop it turning. A load-bearing rope is attached to the nut. In the BNF's reconstruction, a set of pulleys has been included to avoid contact between the raised component and the upright shaft. The upright shaft is turned by manpower by moving the nut to raise or lower the load.

The optimism of the time led some writers to design impossible machines that had perpetual motion and could keep moving permanently without any external energy input. Villard de Honnecourt was not indifferent to this tendency and drew one of the first designs of this type of machine, as shown in Fig. 4.28.

The device in Fig. 4.28 used hammers that, once in motion, would receive sufficient impulse from gravity to keep the wheel in perpetual motion. Underneath the drawing, Villard de Honnecourt wrote: "For some time experts have been discussing how to make the wheel turn by itself. This may be achieved by an odd number of small hammers and mercury in the following way".

After these examples, it is evident that the name "Renaissance forerunner" is more than deserved by this architect-engineer.

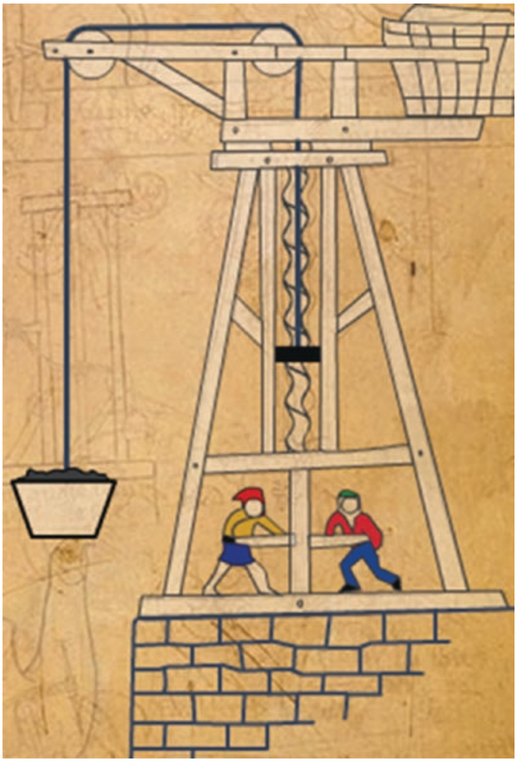

Fig. 4.27 Illustration of Villard de Honnecourt's elevator. Reconstruction by the BNF

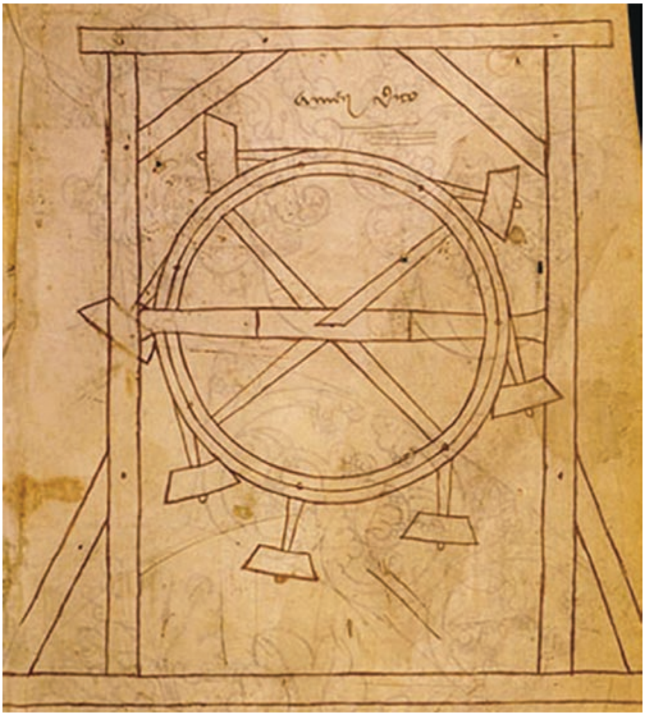

Fig. 4.28 Villard de Honnecourt's perpetual motion device [64]