Functional Analysis of an Animal-Drawn Reaper-Binder

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Walter Franco[0000-0002-0783-6308], Carlo Ferraresi[0000-0002-9703-9395], Paolo Giordano and Giuseppe Quaglia[0000-0003-4951-9228]

Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Torino, Italy
walter.franco@polito.it

Abstract. The development of horse-drawn reaper-binder helped peasants to speed up grain harvesting operations. In the paper, the mechanical architecture, the mechanical power transmission and the main mechanisms of an old McCormick animal-drawn reaper binder are described. A detailed functional analysis of the various mechanisms of the machine, the finger bar mower, the packer system, the needle actuation system, the knotter and the bundle discharging system, is performed. The in-depth knowledge of these historical solutions, also from a functional point of view, can be the starting point for a modern redesign of new appropriate machines.

Keywords: History of Mechanism and Machine, Animal Power, Animal Traction, Appropriate Machines.

1 Introduction

Cereals, being the basis of human nutrition and effectively integrating feeding of farm animals, have been cultivated since ancient times. Among them, wheat has become widespread throughout the world for its good adaptability to different climates, the ease of storage, preservation and transformation in high protein and energy food, as in the case of flour milling for pasta and bread.

For thousands of years, until the beginning of the nineteenth century, the techniques of cultivation of wheat remained almost unchanged: hand seeding, harvesting with sickle or scythes, threshing by animal trampling or with hand flails. All these operations have traditionally required a lot of time and grain harvesting was one of the most intense and time demanding operation of the entire agricultural cycle, together with the soil tilling.

As regard grain reaping, the stone cutters of antiquity, used by foraging societies, where substituted first by sickles, and then by large scythes, documented already since the Roman Gaul (Smil 2017). Unfortunately, cutting with sickles is time consuming. A first innovation was to use scythes equipped with cradles, especially in large fields. It is estimated that a single man was able to harvest (including binding the sheaves) 0.022 ha of wheat field per hour in the case of using the sickle and 0.042 ha/h in the case of use of the cradle scythe (Hurt, 1985). In some cases, harvesting with sickle is anyway preferable because causes lower grain losses, and permit grain harvesting even in small and sloped terrains.

Apart from the curious case of the Gallic reaper, already mentioned by Pliny the Elder (Gaius Plinius Secundus 23-79 A.D.) in the Naturalis Historia and passed into oblivion for many centuries, mechanical reapers appeared in American and European grain fields only in the early years of the XIX century (Aldrich 2002).

At first, animals were used for traction of mowing bars. One of the first efficient reaper was made by Cyrus McCormick in 1834 (Iles, 1912). Two horses, led by a first operator, pull a cart that drives a mowing bar. A second operator, acting next to the machine, rakes the wheat on the ground. Six other men deal with binding the sheaves (Hurt, 1985). A team of eight operators and two horses is able to reap five hectares per day. Around 1860, about 70% of the wheat of the west was mowed by this kind of mechanical harvesters.

Subsequently, the harvesters were equipped with automatic rakes, which allowed carrying out the same work with one operator less.

Later, mechanisms for the automatic tying of the wheat bundles were developed. The sheaves were discharged in the field to be then transported to the farmyard to be threshed. A first binder was probably developed in 1872 by Charles Baxter Withington (Withington, 1872), and in the following decade almost all of the harvest was carried out with automatic reaper-binding machines (Hurt, 1985).

The invention of reaper-binder allowed to considerably reduce the time spent to harvesting and tying the sheaves. Every single operator, working in teams of two, is now able to reaper up to 0.304 ha per hour, more than ten times what it was possible to do previously with the sickle harvesting. The reaper-binder therefore plays an important role in the history of agricultural mechanization.

The paper deals with the functional analysis of an animal-drawn McCormick reaper-binder of 1926. First, the mechanical architecture of the machine is presented. Then, the power transmission of the finger bar mower is shown, with particular attention to the slider-crank mechanism that generates the reciprocating motion of the knife. Finally, the mechanisms actuating the packers, the knotter and the bundle discharging arms are described and analyzed.

2 General mechanical architecture

Figure 1 shows the McCormick reaper-binder object of this study. From a functional point of view, it consists of two main parts: the *cutting system* and the *bundle forming and discharging system.*

The *cutting system,* positioned on the front right side of the machine (Figure 1a), includes the finger mowing bar, the reel and the grain conveyor no longer present on the machine under study. It is designed to mow wheat and to collect it on the conveyor.

The *bundle forming and discharging system*, located on the left side, consists of the wheat packer mechanism, the needle for forming the loop of the cord around the bundle, the knotter and the expulsion system of the bundle (Figure 1b).

A functional scheme of the machine is reported in Fig. 2. The nomenclature and the main characteristics of the mechanical components are reported in Table 1. The numbering of the components cited in the text refers to the scheme of Fig. 2 and to the Table **1**.

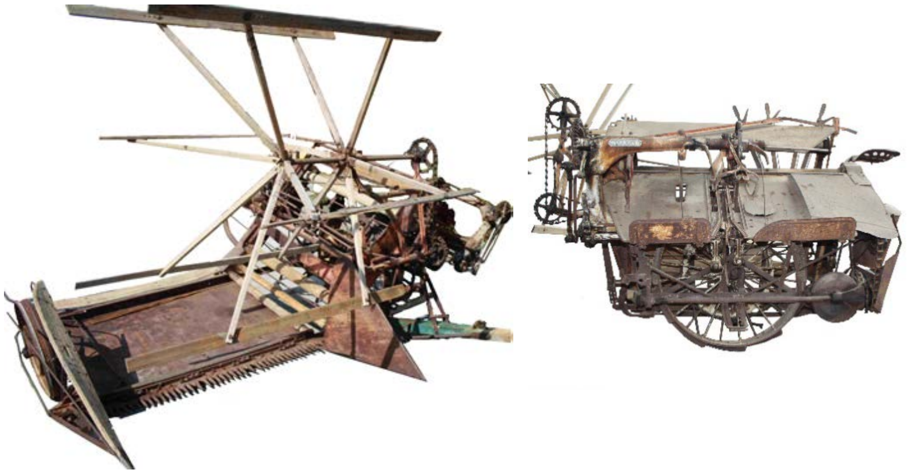

Fig. 1. Reaper-binder McCormick; a) front right side: finger bar mower, reel and grain conveyor zone; b) left side: grain packers, needle, knotter and bundle expulsion system.

Two horses pull the machine at the speed *v*, so that the wheel 1 rotates with velocity ω_1. Wheel 1 is the input link of all the power transmissions and mechanisms of the reaper-binder. A first chain drive consisting of sprockets 2 and 3 rotates the shaft 4. Through the bevel gears 6 and 7 the power is transmitted to the rotating shaft 9 that is the input link of two distinct power transmissions: the one that drives the *cutting system* and the one that drives the *bundle forming and discharging system.* The angular velocity of the shaft 9 can be calculated as:

$$\omega_9 = \frac{2}{D_1}\frac{Z_2}{Z_3}\frac{Z_6}{Z_7}v \tag{1}$$

where D_1 is the diameter of the wheel 1 and z the teeth number of the gears.

Although it was not possible to disassemble the bevel multiplier box of gears 6 and 7, based on the geometry of the box itself its velocity ratio was estimated to be about 2.2. In the case, therefore, of advancing the machine at the rated velocity v=1 m/s, the shaft 9 angular velocity is of about ω_9≈100 rpm.

Between the sprocket 3 and the bevel gear 6 there is a one way jaw clutch 4, whose purpose is to not transmit the motion to the cutter bar and to the binding system when the machine is moved backwards. In addition, the power transmission can be disengaged by means of an appropriate command lever, as shown in detail in Fig. 3.

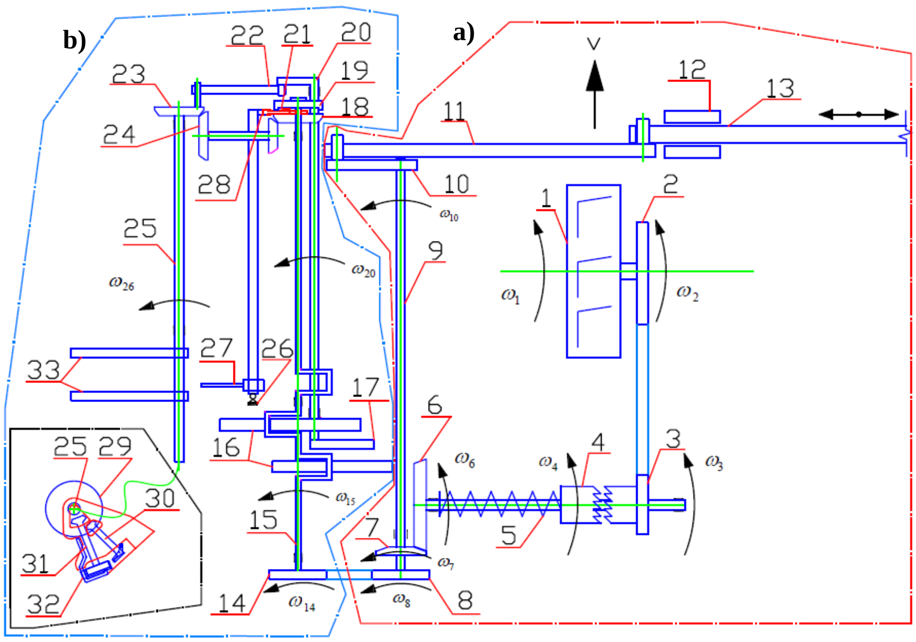

Fig. 2. Functional scheme of the reaper-binder McCormick. a) Cutting system zone. b) Bundle forming and discharging system zone.

Table 1. Components of the power transmission.

#	component name	#	component name	#	component name
1	driving wheel (diameter D_1=875 mm)	12	prismatic joint	23	knotter shaft bevel driven gear
2	driving chain sprocket (teeth number z_2=22)	13	knife of the finger bar mower	24	bevel gears of the knotter shaft transmission
3	driven chain sprocket (teeth number z_3=10)	14	driven chain sprocket (teeth number $z_8\approx 16$)	25	knotter shaft
4	one way jaw clutch	15	crankshaft	26	joint
5	one way clutch spring	16	packers	27	binder tripping arm
6	driving bevel gear (teeth number z_6 unknown)	17	needle	28	binder tripping command
7	driven bevel gear (teeth number z_7 unknown)	18	output clutch bevel gear	29	cam gear
8	driving chain sprocket (teeth number $z_8\approx 16$)	19	rotating clutch member keyed to shaft 15	30	knotter hook
9	shaft	20	needle shaft	31	cord-holder disk shaft
10	crank (length M=80 mm)	21	pawl (dog)	32	shielding flange
11	connecting road (length B=860 mm)	22	needle shaft coupler	33	bundle discharging arms

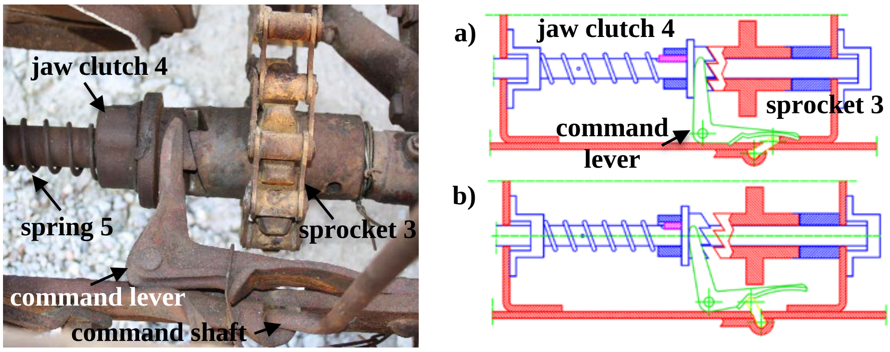

Fig. 3. Particular of the one way jaw clutch and the command lever. a) Connected. b) Disconnected

3 The finger bar mower

The shaft 9 (Figg.2 and 4) is integral with the crank 10 that is the input link of a slider-crank mechanism. The wooden connecting rod 11 is linked to the reciprocating knife 13, that translates in the prismatic joint 12 (Fig.4). The stroke of the bar mower knife, 2 m length, is about 150 mm.

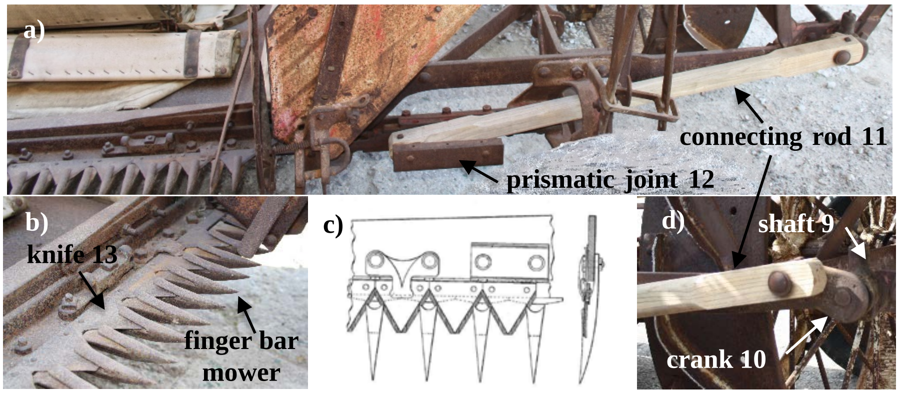

Fig. 4. a) Slider-crank mechanism driving the finger bar mower knife; b) finger bar mower detail; c) Patent US 995902 (Pridmore, 1911); d) crank detail.

4 Bundle forming and discharging system

On the left side of the reaper-binder, the bundle forming and discharging system is located (Fig. 5). It consists of the bundle packers, the needle, the knotter mechanisms and the bundle discharging system. All the mechanisms are driven by the rotating shaft 15 (Fig. 2), which in turn is actuated by the chain drive consisting of sprockets 8 and

14. During the advancement of the machine, the shaft 15 rotates at the same angular velocity of the shaft 9, given by the Eq. (1), because the number of teeth of sprockets 8 and 14 is the same.

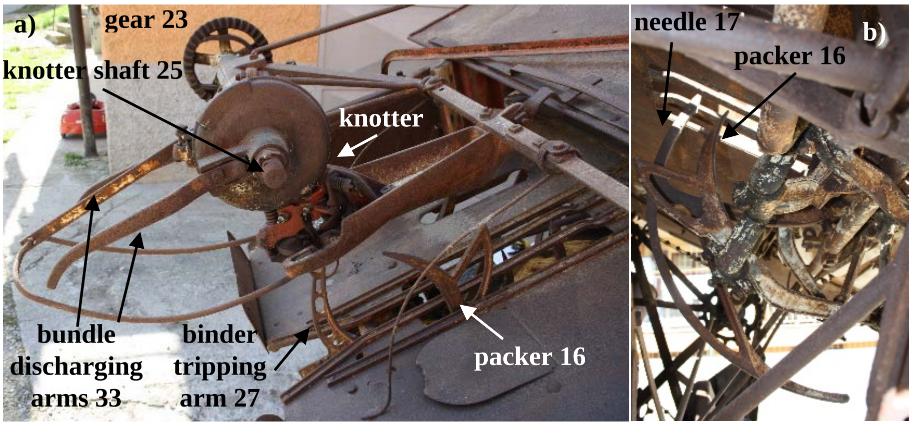

Fig. 5. Bundle forming and discharging system. a) Bundle forming area. b) View of the mechanisms on the underside of the machine.

4.1 Bundle packers and binder tripping

The wheat, collected in the area near the cutter bar by the reel, is brought into the bundle forming area by a conveyor, no longer visible in the machine under study. Here it is accumulated against the binder tripping arm 27 thanks to the action of two packers (Fig.5). Each packer is a coupler of a four bar linkage, driven by the crankshaft 15. Figure 6 shows the drawing of the mechanism reported in the Patent US767412 (Johnston, 1904) and the positions assumed by the packers (red and green) for different angular positions of the crankshaft (light blue).

Once the bundle has been formed, the packers action is transmitted on the binder tripping arm 27 (Figs 2 and 5), whose roto-translation motion causes the start of the binding phase. The latter in turn occurs in two phases: the formation of a cord loop around the sheaf by means of the needle and the knotting phase.

Figure 7 shows the functioning of the clutch pawl responsible for starting the bundle binding and discharging phase (Benjamin, 1911). When the bundle is completed, the packers 16 (Figg. 2 and 5) push the binder tripping arm 27 (Fig. 7), which drags the curving clutch tipping member (in green). The pawl 21 (in red) can thus rotate, and the clutch is engaged. In this way, the motion is transmitted from the crankshaft 15, integral with the rotating clutch member 19, to the bevel gear 18. Through the bevel gears 24 and 23 (Fig. 2), the entire binding system is driven, as described below.

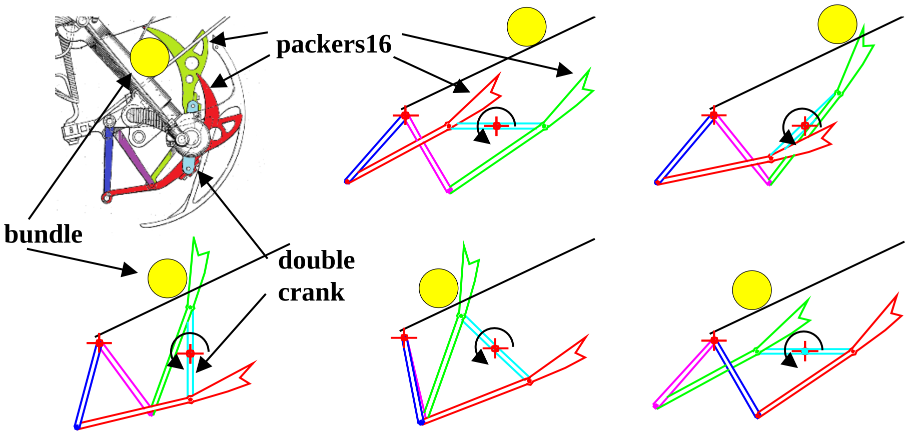

Fig. 6. Packers of the Patent US 767412 (Johnston, 1904) and the simulated sequential positions of the packers for different angular positions of the crankshaft (half crank revolution).

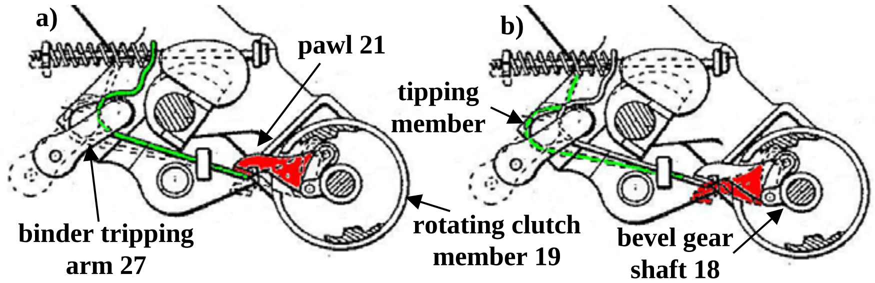

Fig. 7. Functioning of clutch pawl for activation of bundle binding and discharging system (Benjamin, 1911). a) Disengaged. b) Engaged.

4.2 Needle shaft mechanism

Once the binding/discharging phase of the bundle has been started, the pawl clutch transmits the motion to the bevel gear 23, through the shaft 24 (Figg. 2 and 8).

The wheel 23 is also the crank of a four bar linkage, whose rocker is integral with the needle devoted to forming a cord loop around the sheaf. In Figure 9 the positions assumed by the needle for a complete rotation of the wheel (crank) 23 are shown.

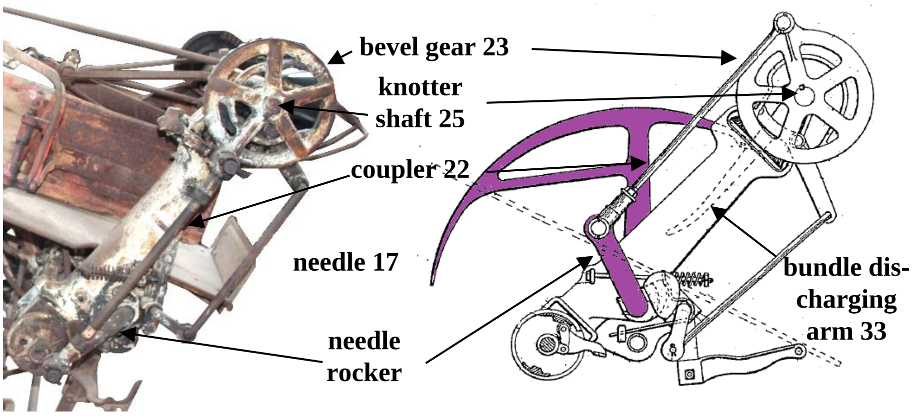

Fig. 8. Crank-rocker four bar linkage for the actuation of the needle. a) Machine under study; b) Patent US 994711 (Benjamin, 1911)

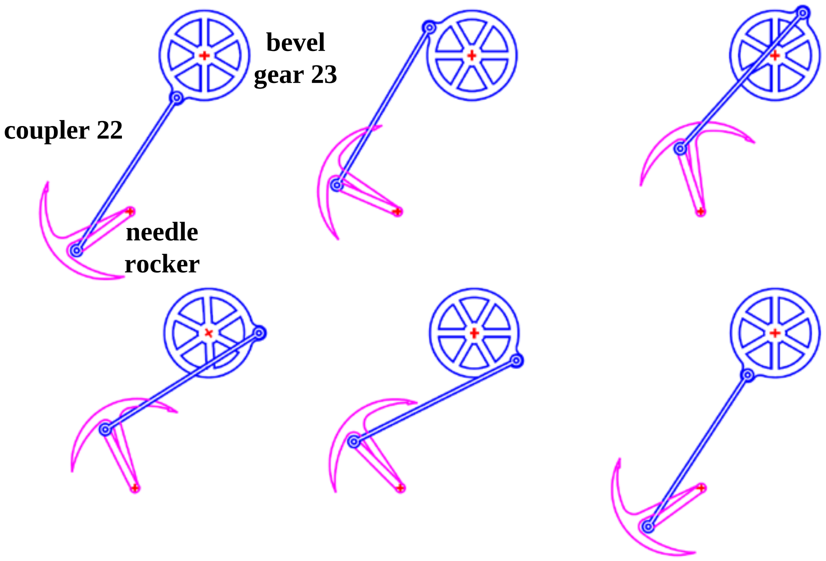

Fig. 9. Simulated sequential positions of the needle versus the rotation of the wheel 23.

4.3 Bundle knotter and discharging mechanism

The wheel 23, in addition to driving the needle 17 through the coupler 22, rotates the shaft 25, to which it is integral. The latter, on one side, drives the knotter, on the other side causes the rotation of the discharging arms of the bundle 33, which projects the sheaf into the field once bound (Fig.5).

The knotter binds the cord around the sheaf, after the needle has brought the other end of the cord in its vicinity making a loop around the bundle, as shown in Fig. 10. The knotter consists of the cam gear 29, driven by the shaft 25. The cam gear 29 is arranged in order to actuate the knotter-hook 30 and the cord-holder shaft 31 through corresponding pinions. The transmission is arranged so that each revolution of the cam-gear disk 29 corresponds to one revolution of the knotter- hook 30, that knots the cord, and to one half revolution of the cord holder disk 31, with the purpose of dragging and cutting the cord.

A side elevation view of a knotter-hook of the Patent US 1523471 (Benjamin, 1925) is shown at the top left of Fig. 11. It consists of two hinged parts: the hook and the tongue pivotally mounted on a pin. Again in Fig. 11, the binding sequence is visible. During rotation, the knotter-hook intercepts the two cords, the one detained by the cord-holder, and the one brought into the area by the needle. In its final phase of rotation, the knotter-hook tongue, whose roller follower is commanded by a cam, is raised in such a way as to pinch the cord between itself and the hook. In the next phase during the bundle discharging, the knot is completed.

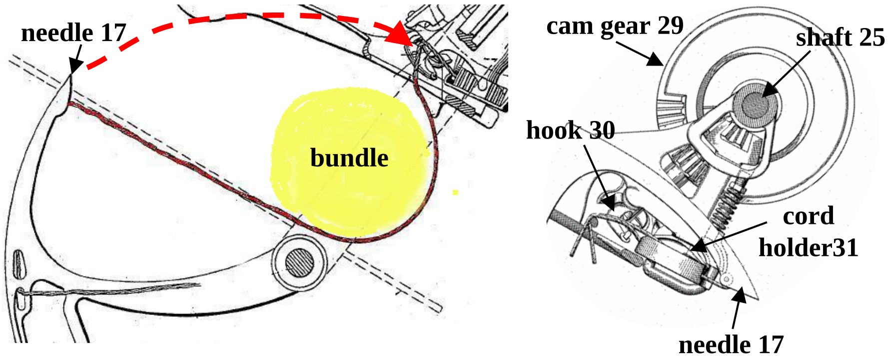

Fig. 10. Knotter. a) Cord loop forming by the needle (Coler, 1898). b) Cord older of the Patent US 865754 (Benjamin, 1907)

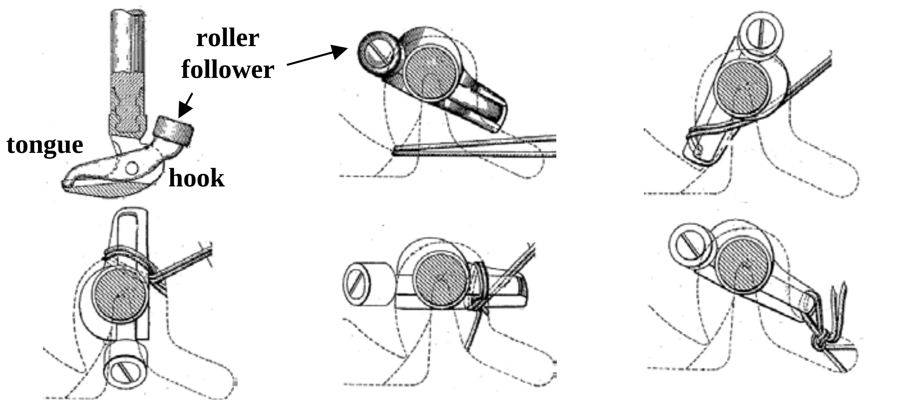

Fig. 11. Side elevation view of knotter-hook of Patent US 1523471 (Benjamin, 1925), and plan views in successive stages of knot tying operation in Patent US 500608, (Phelps, 1893).

5 Conclusions

For thousands of years, grain harvesting operations have been carried out manually, using simple sickle or scythes, so that they required very long times. The introduction, first of simple mowing bars, then of animal-driven reaper-binder, allowed to reduce considerably the time dedicated to harvesting the wheat. For this reason, animal-powered reaper-binder played an important role in the history of agriculture mechanization.

In the paper, a functional analysis of the power transmissions and the main mechanisms used on an animal-driven McCormik reaper-binder of 1927 has been conducted.

Beyond the historical value of the work, there is a renewed interest in this type of technology, able to combine high productivity (0.6 ha/hour) and low consumption of renewable energy (2.65 kW h/ha against 14.70 kW h/ha of a modern tractor mounted reaper-binder).

The reaper-binder under study represents an important technology of the past, which may be a hint for redesigning of new low-tech technological solutions for family peasant agriculture, both in developing countries – for example in low income communities - and in western countries – for instance in the cases of energy transition practices (Ferraresi, 2011; Franco 2017).

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