Friulian Journal of Science **35.** 2023, 23-35

Equipment to Improve Work in the First Three Stages of the Silkworm: Design, Prototyping, Construction and Testing

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Abstract. Silk is a protein fibre derived from the cocoon produced by the silkworm *(Bombyx mori)*. It is very light, lustrous and delicate to the touch, and has a long shelf life and high affinity for dyes. Currently, 95 per cent of global silk production occurs in Asia, particularly China; but even there, production is now declining in favour of synthetic fibres.
Sixty per cent of all plastic used, such as polyester, polyamide, acrylic, etc., is found in clothes. When these clothes are processed mechanically (e.g., in a washing machine) they release large amounts of these small plastic particles, which then end up in the water, the sea, and even in the air. This situation has seen all countries move towards a return to natural fibres, and much scientific research has been initiated to enable the redevelopment of silk production and its market through these conditions.
To help the rebirth of the silk sector, the Friuli Venezia Giulia region, through the 2014-2020 RDP, has funded the "SILK" project. As part of this project, the Biosystem Engineering research group of the Department of Agri-Food, Environmental and Animal Sciences at the University of Udine took on the challenge of devising and designing a new prototype machine to help work during the early developmental stages of silkworms. The prototype, built for the first three stages of silkworm rearing, is a step in the direction of devising and designing tools that increase the ergonomics and productivity of work and that could also be used on small farms.

Key words. Silk, silkworm tools, machine design, silkworm rearing.

1. Introduction. Silk is a protein fibre derived from the cocoon produced by the silkworm *(Bom byx mori)*. It is very light, lustrous and delicate to the touch, and has a long shelf life and high affinity for dyes. The raising of

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Table 1. World silk production (in tons).

Country	*2014*	*2018*	*2020*
China	146,000	120,000	53,359
India	28,708	35,261	33,77
Uzbekistan	1,100	1,800	2,037
Vietnam	420	680	969
Thailand	692	680	520
Brazil	560	650	377
North Korea	320	350	370
Japan	30	20	16
Turkey	32	32	5
Italy	3.5	2.8	2

silkworms with silk as the end product is called sericulture. Currently, 95 percent of global silk production occurs in Asia, particularly China (Tab. 1); but even there, production is now declining in favour of synthetic fibres.

In Friuli and neighbouring Veneto, silkworm breeding began around 1400 to 1500 when the Republic of Venice began producing, weaving and exporting silk. As is already known, the silkworm feeds only on the leaves of the mulberry tree *(Morus*, family *Moraceae*) – ideally *Morus alba* but also *Morus nigra* – and, thus, in the same historical period, people started planting many mulberry trees, often along the rows of vines to support them, leading to a rapid transformation of the Friulian landscape that persists to the present day (Fig. 1).

Toward the end of the 1700s, a Friulian economist, Antonio Zanon, realised that it was better to produce the cocoon on family farms instead of on the estates of the lords; this was an idea that Jacopo Linussio had already developed in Carnia to produce clothes in families, using the very important work of women. This innovation led to a very rapid development of silkworm breeding throughout Friuli and also in the Veneto region. The first major crisis in silk production occurred around the 1930s (Fig. 2), when Mussolini's regime introduced laws to encourage autarky; this disfavoured the silk market, which was almost entirely aimed at exporting to foreign countries, and resulted in a significant reduction in the income of these farming families.

After World War II, the silk produced in Friuli cost much more than that coming from the East, and so it began to die out. It should be remembered that in 1924 57,000 tons of cocoons were produced in Italy, which dropped to 13,000 in 1950, to 7,000 in 1959, and almost disappeared around 1970.

Figure 1. Mulberry trees in Gemona in winter.

Figure 2. Delivery of cocoons to Gemona around 1930.

Around 1990, many strategies were attempted to revive silk production. These failed, however, partly because of a poison *(fenoxycarb)*, used in agriculture to protect apple, peach and other fruit trees from butterflies *(tortricidae)* but which ended up also on mulberry trees, thus killing the silkworms that ate the mulberry leaves. In 2012 this product was banned, but silkworm breeding still failed to restart, despite increasingly less silk also now being produced in China due to rising labour costs and a work transition of millions of people from agriculture to other sectors. Thus, as was the case here in Friuli, silk production remained the same as it was 100 years earlier.

The fact that China no longer produces enough silk, could represent an advantage for considering the redevelopment of sericulture here in Friuli, taking into account the serious global problem of increasing nano- and microplastics. Plastic materials are used on a daily basis and are found in bags, furniture and food packets; they are also used in place of iron, wood, paper, glass, etc. because they are lightweight, durable and inexpensive.

To give an example, 60% of all plastic used, such as polyester, polyamide, acrylic, etc., is found in clothes. When these clothes are processed mechanically (e.g., in a washing machine) they release (Salvador Cesa et al. 2020) large amounts of these small plastic particles, which then end up in the water, the sea, and even in the air (De Falco et al. 2020). This situation has seen all countries move towards a return to natural fibres, and much scientific research has been initiated to enable the redevelopment of silk production and its market through these conditions (Singh, Nigam, Kapila 2021):

– mechanisation of mulberry cultivation and harvesting of leaves to prepare them for silkworms according to their age;
– support in silkworm rearing with equipment to decrease labour hours and labourer fatigue.

As we saw in Table 1, production is declining everywhere, mainly because the breeding technique has remained the same and production can now no longer stay within costs (Hatibaruah et al. 2021). In India and China too, attempts are being made to change the age-old way of raising silkworms, by incorporating a technique that washes the trellis or improves the cleanliness of the whole system (Li et al. 2017).

With the combination of equipment used to improve silkworm rearing, a 65 percent decrease in labour hours and a 55 percent increase in productivity (kg silk/ hour) has been seen. The cost of silk in this case decreased by 35.9 percent (Jung et al. 2006).

Another problem that needs to be solved is the overly-large space used in old-fashioned breeding; a smaller, less costly space is now required.

To help the rebirth of the silk sector, the Friuli Venezia Giulia region, through the 2014-2020 RDP, has funded the “SILK” project. This aims to activate “silk districts” where – alongside the design of new breeding machines – thought is also given to how to improve mulberry cultivation through the study of those trees still growing within the Friuli territory as well as the planting of new mulberry fields, perhaps with plants that will develop as early as early spring into late summer. At one time, in fact, worms were raised only in the month of May, after which the farmers would return to mowing hay and other work.

Table 2. Normal measures for rearing poly-crossed silkworms (20,000 eggs) (Cappellozza, 2010).

Moults	*Required area in m^2*		*Mulberry leaves*	*Temperature*	*Humidity*		Duration	
	At the beginning of the stage	*At the end of the stage*	*kg*	*Co*	*At the beginning of the stage*	*During moulting*	*Days*	*(+) moult days*
1st instar stage	0.4	0.8	1.5-2.0	27	90	65	4-5	(+) 1
2nd instar stage	1.0	1.8-2.0	3.0-4.0	26	85	65	3	(+) 1
3rd instar stage	2.0	3.6-4.0	15-20	25	80	65	4	(+) 1
4th instar stage	4.0-4.5	8.0-10.0	65.0-70.0	25	75	60	5	(+) 1
5th instar stage	10.0	15.0-20.0	300.0-340.0	24	70	70	7-8	
Total	-	-	384.5-436.0	-	-		27-29	

This was also because there was no way to control the temperatures and humidity, which in silkworm rearing must remain within precise values (Tab. 2). Instead, breeding could now be extended to cover the entire season from May to October, using, for example, an air conditioner to control environmental conditions and a mulberry cultivation designed to provide a sufficient source of leaves, so enabling the production of four or five generations of silkworms instead of just one.

Alongside these goals, there is also a drive to develop new ways for using silk and its products, such as cosmetics or other beauty solutions.

As part of this project, the Biosystem Engineering research group of the Department of Agri-Food, Environmental and Animal Sciences at the University of Udine took on the challenge of devising and designing a new prototype machine to help work during the early developmental stages of silkworms.

2. Methodology. The goal of the project was to build a tool that would help the operator work better in the first three stages of the silkworm, which are the most difficult to manage because the worms are in a larval state, very small and weak, and require great care in their management. The basis of this idea was that, in any silk district, a company would take on the rearing of the first three stages of the silkworm when they required careful feeding, shredding the leaves into small pieces and regularly cleaning (once or twice a day) the frame where they eat of leaf waste, dirt and dead specimens. Once the third stage of this delicate process was over, the worms would be given to other farms to finish the cycle comprising the last two stages, where they could be raised on the ground – needing more space but, being now bigger and stronger, less care.

What the design required for the construction of the prototype of this tool can be summarized as follows:

1) a machine to facilitate operations where one or two workers can work

sitting ergonomically or standing but without having to move;
2) manage at least one ounce (60,000 eggs) (Tab. 2);
3) to help clean silkworm frames and reduce work time;
4) comfortably feed silkworms;
5) easily control the temperature and humidity;
6) comply with the Workplace Safety Act.

The design of the prototype began in the spring of 2018, with the first drawings done by hand as sketches. The work was then reproduced in AUTOCAD, taking into account the measurements required for the environment in which the prototype would later be installed, namely Alessio Sverzut's *Comugnâi* company in Aquileia.

The room measured 2.75 metres in height, 6 metres in length and 3 metres in width.

Since the entrance door was only 2 metres by 2 metres, the tool was designed so that it could be disassembled into several pieces to facilitate its entry, and then reassembled inside the room.

Once the design was finished on AUTOCAD, the drawing was taken to the mechanical carpentry factory of Ferruccio Pezzetta of Buja (Friuli Venezia Giulia) for construction, playing around with the parts a bit and using standard sizes in order to lower production costs.

The prototype was then built and brought to the farm in Aquileia where there was already a small silkworm farm. Once mounted in the room intended for its use, it was trialled from the fall of 2021 to the spring of 2022 on half an ounce (10,000 eggs), thus using a lower quantity than the prototype's capacity for raising silkworms (the project, as we said, is designed for 60,000 eggs). This reduction was necessitated by a dry season that produced few mulberry leaves.

3. Results. A first result is definitely the construction of the prototype itself, based on the design drawn in AUTOCAD (Fig. 3 e Fig. 5a e 5b) and the objectives listed in the methodology paragraph.

To answer the six questions that emerged when the prototype was designed, the following solutions were chosen for each of the points presented in the methodology:
1) to achieve the first objective, a wheel was designed with multi-level boxes, so that as they turn, they can be used one at a time, allowing good use of the square meterage of the room where the machine is to be placed. By rotating these boxes, you would only need one worker operating, who would not need to move around much. The boxes can be locked to enable a worker to operate both standing (at 1000-1200 mm above ground level) and sitting (at 700-800 mm above ground level) depending on the need at that moment.
2) for the second objective, the area needed for the third stage of the silkworm was calculated and it was found that at least eight boxes of 1.5 m^2 were needed for a final count of 12 m^2 (Fig. 3);
3) to be able to clean the boxes well, they were produced in stainless steel (AISI 304), measuring 2,500 mm x

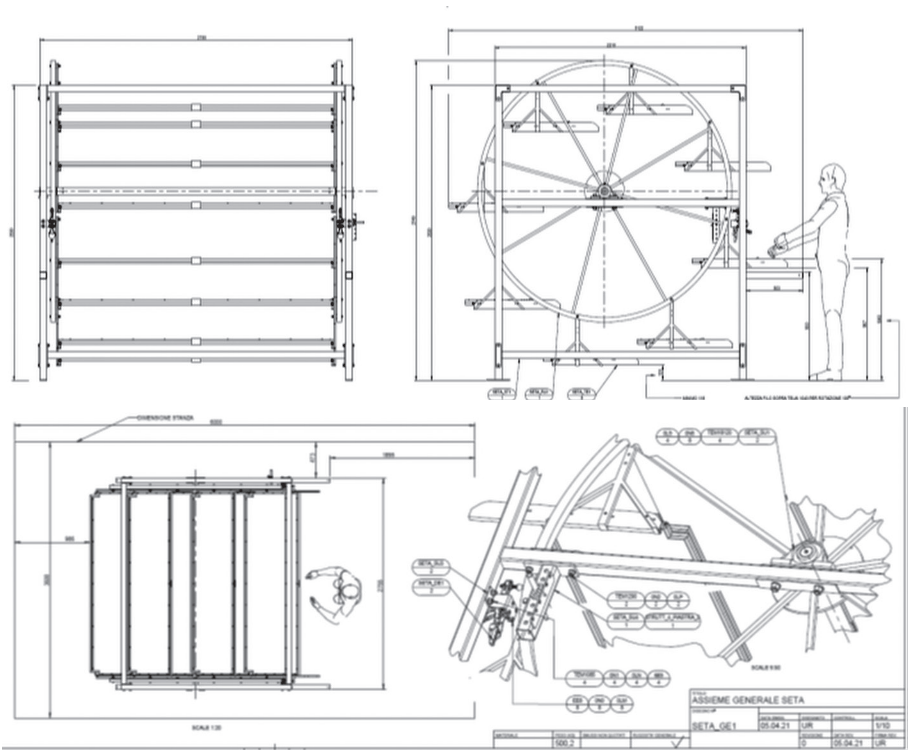

Figure 3. Drawing of the prototype.

600 mm, and were attached to a steel frame. These boxes have four small wheels attached to the four corners, which can be easily removed or re-attached, making it possible to tip them over to dump dirt into a bucket or to clean them well using a vacuum cleaner. Threaded rods were inserted every 200 mm along the top of the frame that supports the boxes (ø 5 mm x 50 mm high), so as to be able to tie a fiberglass net, such as those used in construction, with a mesh of 11.0 x 10.0 mm or even 5 x 5 mm, depending on the size of the silkworms. It is possible to place washers on the threaded rods so as to be able to change the distance of the net from the bottom of the box, depending on the age of the silkworm, so that as they grow one can raise the net. Initially, the silkworms are placed on a sheet of paper on top of the net, and on this sheet the leaf is placed so that the silkworms can climb onto it to eat. When they are given food again, one places another paper sheet on top of the net and lays the worms on it, meanwhile cleaning the box. The net is then placed back on top

and so on. At this point, dead or weak silkworms or silkworms that have not moulted like the others (laggards) are checked. With each passage, the bubble occupied by silkworms widens because they grow fast;
4) during the first three stages, one should feed silkworms with shredded leaves, very thin at the first stage, then somewhat larger as they move from one stage to the next (at the fourth stage, one can also give them mulberry buds or shoots). With the spinning wheel system, there is no need to move trellises or boards but shredded leaves are collected from a basket near the worker and thrown over the net so that the worms can climb and eat. All of this is done very quickly because you have everything you need; you just spin the wheel and thus go from one box to another;
5) in order to attain good results in silkworm growth, it is important to control the humidity and temperature. This can be achieved with good ventilation between the boxes, which are, in fact, positioned to allow good air recirculation, so avoiding a big difference in these two parameters between the lowest and highest point of the wheel;
6) one of the last goals in assembling the prototype was to solve the problem of safety. Being a machine with a wheel that turns on a frame and which must be locked very well when working on a box, three safety systems have been installed (Fig. 6a e 6b): two brakes (one on each side of the wheel, left and right) resting on the frame to stop the wheel, and two stops to be able to work safely even if the brakes malfunction; a third stop is placed at the level of the box so that it does not wobble when working on it. Again, with safety in mind during work, it was decided not to install an electric motor to turn the wheel, although it will be possible to provide for this in the future, as the project costs would have escalated too much, especially to implement other safety control systems during wheel movement. Trials to test the operation of the prototype were done by rearing silkworms for two seasons, albeit to a reduced extent compared to the machine's potential, but these initial trials showed that work time and fatigue decreased significantly.

The problem of the farm not having sufficient mulberry leaves meant that full trials of the prototype could not be conducted; however, it was possible to verify an ergonomic improvement in the work process. The wheel with eight boxes, measuring 2,500 mm x 600 mm, works satisfactorily in the room where it was placed. The boxes, which are made of stainless steel, clean very well, as claimed by the owner of the company who worked with the silkworms and used a vacuum cleaner. The fact that one can extract and reposition them with the help of the wheels means one does not have to exert too much effort and can work quickly (Fig. 7). The presence of threaded bars on the edges of the boxes to easily attach the net and paper are fine but some crossbars should be added so that the net does not bend under the weight of the silkworms and does not touch the bottom of the box in the centre (Fig. 4).

It should be noted that the two safety systems (Fig. 6a e 6b) installed

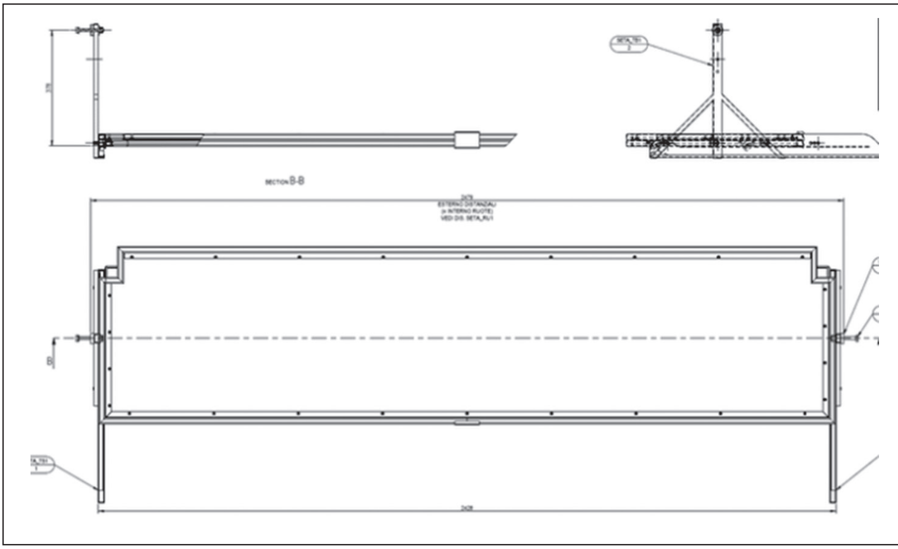

Figure 4. Drawing of the stainless steel box.

on the machine are very important to avoid the risk of someone getting trapped in the wheel and frame while the wheel is turning during work; they work well and are not too complicated to use. Furthermore, one does not waste too much time placing and removing them.

4. Conclusions. As is well known, silk production is very important in the textile industry for quality clothing, particularly in Italy, which is one of the main markets for high fashion. Another area that may offer great potential and new uses is the pharmaceuticals and skin and body care *(beauty)* sector. In order to supply this market – which still buys materials from China – Friuli and Veneto would need to return to significant silk production, and this could only be achieved with tools that increase the ergonomics and productivity of work. The prototype built for the first three stages of silkworm rearing is a step in this direction and could also be used on small farms. This, then, should be just one of the initial tools and machines for starting the entire supply chain to achieve innovative and competitive silkworm breeding, and so produce local silk instead of buying that which comes from other parts of the world. For this reason, to complete the supply chain, one could think of machines for detaching the leaves from the mulberry branches, removing impurities from the cocoons (a process previously done by hand), cutting the leaves into different sizes according to the stage of the silkworm, and so on.

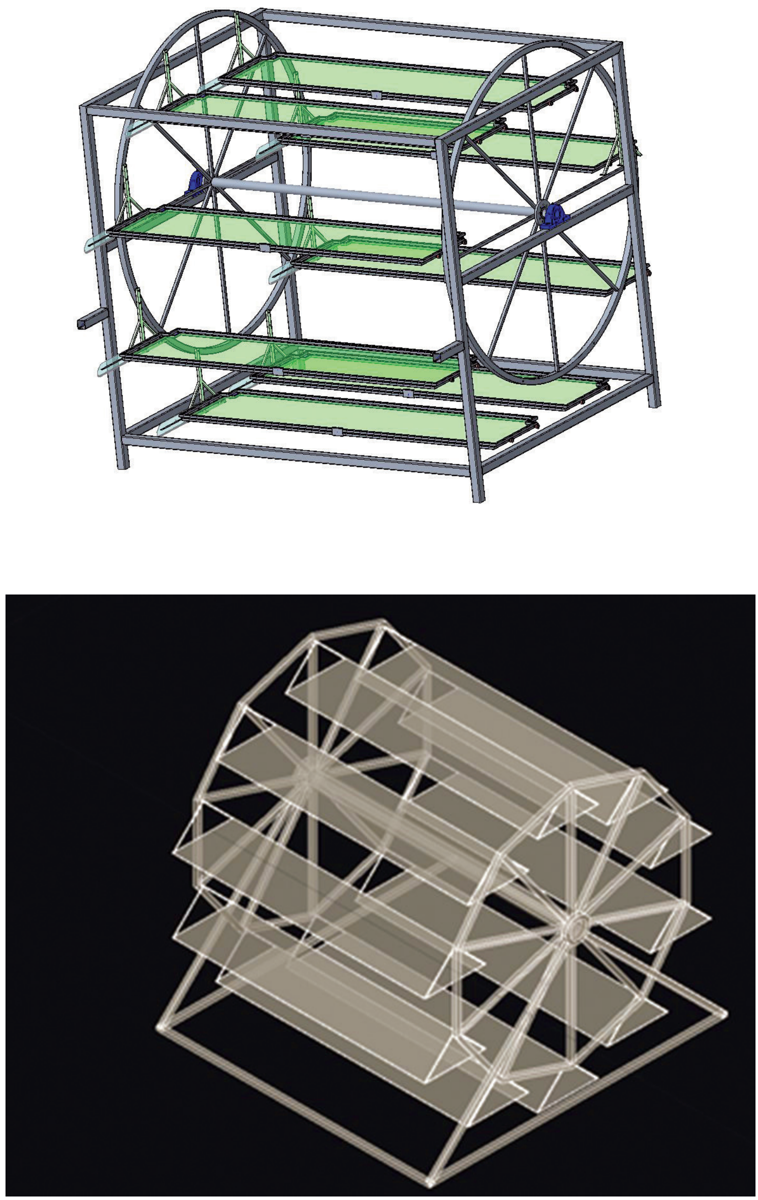

Figure 5(a) and 5(b). 3D visualisation of the prototype.

Figure 6(a) and 6(b) In red are the safety systems mounted on the machine: brakes, fork stops on the wheel and the box frame so that they do not wobble while working, and fork stops on the square spoke of the wheel to prevent it from moving while working on the box. Two hinges can be seen on the boxes to stop the bottom from sliding out.

Figure 7. Detail of the hinge to hold in place the bottom of the stainless-steel box with casters.

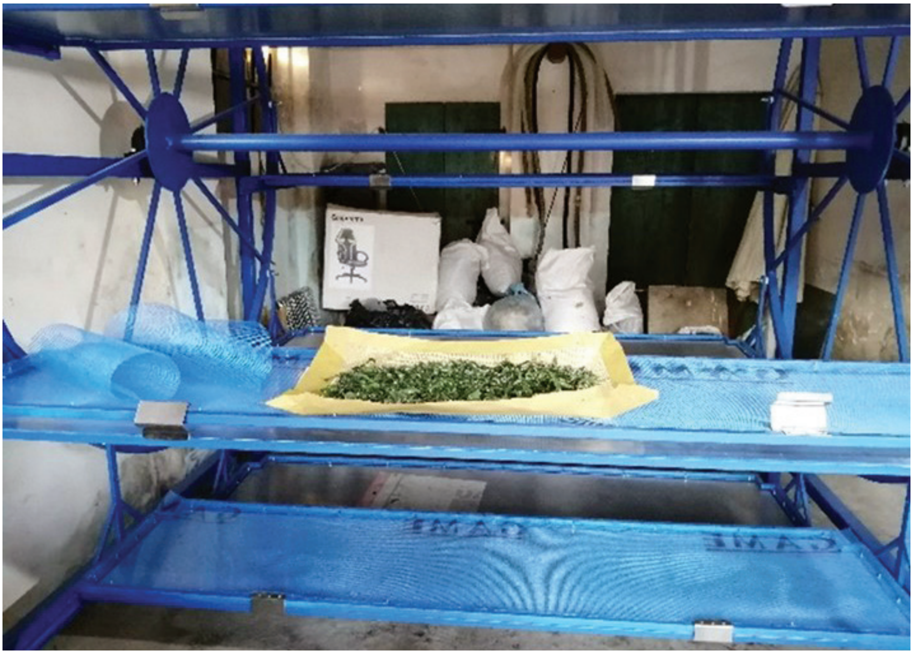
Figure 8. First test with silkworms from half an ounce of eggs in the first stage.


Figure 9. Test of the equipment.

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