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Developing a Novel Fully Automated Concept to Produce Bowden Cables for the Automotive Industry

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Abstract: The automotive industry is one of the driving forces of the global industry; thus, it is a very competitive sector which creates a constant need for process improvement, regarding productivity, quality, and flexibility. Automation has proven to be a viable solution for these production problems, with the rising adoption of these automated system by companies that try to design and implement more flexible systems, while reducing costs and improving process quality. Furthermore, the use of automation reduces the manpower factor and its associated variability. In the present work, a new concept for a Bowden cable production process is presented by employing the design science research (DSR) methodology. The project starts with the analysis of the previous production concept, determining possible problems and improvements, as well as setting objectives/requirements for a possible new concept/equipment. This information was used to develop a new automated Bowden cable production equipment, implementing several changes to the old concept and filling a gap in the literature in this field. The developed system was implemented and tested. A considerable reduction in cycle time was registered by 25%, which resulted in an increase of 30% in process productivity.

Keywords: Bowden cables; automotive industry; automation; process improvement; flexibility; productivity

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Citation: Sousa, V.F.C.; Silva, F.J.G.d.; Campilho, R.D.S.G.; Pinto, A.G.; Ferreira, L.P.; Martins, N. Developing a Novel Fully Automated Concept to Produce Bowden Cables for the Automotive Industry. *Machines* **2022**, *10*, 290. https://doi.org/10.3390/machines10050290

Academic Editors: Kai Cheng, Mark J. Jackson and Hamid Reza Karimi

Received: 26 March 2022
Accepted: 19 April 2022
Published: 21 April 2022

1. Introduction

The automotive industry remains one of the main driving forces of the global industry, as mobility is one of the most important characteristics of the current lifestyle. Due to its importance, the automotive industry is a very demanding sector, with the constant need to increase productivity and revenue [1,2]. Moreover, research conducted regarding the automotive industry is quite a popular topic, especially about optimizing certain manufacturing processes [3,4]. There are also some studies regarding the improvement of quality and productivity [5] of automotive component assembly lines [6] by applying Lean methodologies [7,8]. Aluminum and zinc alloys are commonly employed in the automotive industry, with Zamak being quite used. As such, there have been some recent studies about the improvement of the casting [9,10] and injection of these alloys [11]. These alloys are particularly used in the production of components such as Bowden cables. There have been studies conducted about the improvement of these processes as well, as the production of these cables is quite labor-intensive, having room for improvement. There are also some problems associated with these cables after production, such as corrosion problems. The study of this corrosion helps to mitigate these problems, ensuring the quality of the produced Bowden cables [12,13].

The existing challenges for the automotive industry are quite demanding, focusing on cost reduction and increased competitiveness, without performing a big additional investment [14,15]. As such, manufacturers look to outsource their responsibilities, particularly in areas such as development, procurement, and planning [14–17]. This increasing demand causes the suppliers to lower their prices, while meeting strict quality and delivery deadlines [18–20].

Currently, there is a growing need for flexibility when it comes to manufacturing processes; this is, there is a need for highly customized products [21]. This means that companies need to adapt and increase the flexibility of their processes [22–25], producing a wide variety of products, thus maintaining their competitiveness in the market [26]. However, this is a challenging task, as the increase in product variety tends to affect delivery times (albeit dependent on the product), which play an extremely important role in the company's competitiveness. As such, the automotive component manufacturing industry invests highly in the research of new solutions and strategies aimed at improving the efficiency and competitiveness of various manufacturing processes [27–29]. Process automation plays an important role in this area, reducing the dependence on human labor, reducing production costs, and increasing overall process productivity [30–32].

Many examples of automation applications can be found in industrial production lines, such as industrial production control systems with feedback, mechanized assembly lines, and industrial robots [33–35]. Many benefits may arise from the correct automation application, especially for the production process, as it may lead to a setup time reduction, productivity increase, and production quality increase, while reducing overall costs [30–32], manpower, number of required production operations, and delivery times [24]. The reduction of manpower may pose a problem, as it may cause the workers to become unnecessary. However, this is not always the case, as the extra workers may be used for different operations that require more responsibility.

The use of robots in the automotive industry is also quite common, performing quite well in different stages of vehicle production and assembly [36,37]. However, the implementation of robots is not always the best case, as several studies show that, in some cases, a correct use of automation can improve productivity and reduce cycle times, without the need for expensive robotic solutions [24]. Silva et al. [38] developed an automated bent wire feeding system for an over-injection machine to produce automobile seats. Only automation was considered in this case, due to space and budget constraints. The reutilization of unused automation components was promoted, increasing the sustainability of this solution. Figueiredo et al. [39] presented a study in which the introduction of a stripping operation in the Bowden cable production process allowed them to transform a semi-automatic equipment into a fully automatic one, with a return on investment estimated at 2.3 years, which is quite low. Moreira et al. [40] developed a new approach of joining different manufacturing and assembling operations in a single production cell. Moreira et al. concluded that, through the appropriate mechanical design and automation processes, it is possible to promote the integration of subassembly operations, increasing process productivity and flexibility, while reducing problems associated with product quality. Studies such as the ones that were presented in this paragraph highlight the potential of the proper application of automation in manufacturing processes. The use of automation brings many advantages, such as a reduction in machining operation cost [41] and a reduction of maintenance costs and equipment breakdowns [42], and it is related to an overall increase in process productivity [43].

There is a crescent need for more productive and flexible solutions, especially by equipment manufacturers in the automotive industry. Customization is increasing drastically in detriment of mass production, causing the need for equipment that is able to deal with a relatively wide range of products, within the same family, but having different features, components, and dimensions, or even requiring a different operation sequence for its production. In the present work, a newly developed fully automated Bowden cable production process is presented that is able to produce three different cable types and twenty-four different cable references (having different dimensions). For the development of this novel concept, the design science research (DSR) methodology was employed, which comprises of six stages: (1) problem identification, (2) definition of objectives for a solution, (3) design and solution development, (4) demonstration of the solution, (5) evaluation of the proposed solution, and (6) drawing conclusions [44–46]. This work shows that the correct study of a problem and the clever implementation of automation in a production process enable an increase in production and a reduction in cycle time, without the need for more expensive implementations, such as the use of robotics.

2. Materials and Methods

As previously mentioned in the present work, a new concept for Bowden cable production equipment is presented here. This equipment was designed based on a previously implemented cable production concept, offering an improvement over this previous equipment. The DSR methodology was adopted in the development of this work, based on published works of authors such as Vaishnavi and Kuechler [44]. This methodology is usually adopted when developing new concepts from existing ones [45,46]. Since, in this work, the presented concept was developed based on an existing Bowden cable production process, this methodology was adopted. The development of this new concept can be divided into six stages; these stages and their description are presented in Table 1.

Table 1. Contents of each step of the DSR methodology used in this work.

Step	Description
Problem awareness	Analysis of the previous concept, determining various problems and aspects that can be improved
Define objectives for a solution	Define various objectives/requirements for a solution for the identified problems
Design and development	Based on the requirements, design and develop new solution
Demonstration	Implementation of the developed concept
Evaluation	Evaluate the performance of the developed solution, verifying if the set requirements were met
Conclusions	Final evaluation of the solution, offering a comparison between the previous and newly developed concepts

As seen in Table 1, the project starts with the evaluation of the previous production concept, identifying possible problems/improvements. In the following subsections, the first three stages of the DSR methodology adopted are going to be presented, starting with the previous concept analysis, followed by the requirements/objectives set for the new concept, and finally an introduction to the new developed concept is made. As for the last three DSR steps, these are presented in Sections 3 and 4.

2.1. Analysis of the Previous Concept

In this subsection, an analysis of the initial Bowden cable production system used is presented. The cable production equipment is not fully automated, and it performs four crucial operations; it then sorts these cables as OK or NOK at the end of the process. These operations are presented in Table 2.

The equipment responsible for the operations performed in the cable's second terminal is depicted in Figure 2.

This equipment can produce three distinct types of Bowden cables, namely IBT, IBT LASSO, and ZZH, as depicted in Figure 3.

These cable types have multiple references, with slight variations in length or configuration. The equipment produces twenty-four different references, with the ZZH cable type having twelve references, the IBT type having eleven references, and the IBT LASSO having only one reference.

Figure 1. Mushroom performed in different cables.

Table 2. Operations performed by the initial Bowden cable production equipment.

Operation	Description
Mushroom making	Performs a mushroom at the tip of the cable (Figure 1), preventing the cable from sliding into the Zamak injected part
Terminal injection	Injection of the Zamak terminal
Validation tests	Performance of tensile-strength and length-measurement tests, determining if the cable satisfies the requirement to advance for the next stage
Sprue-cutting and extraction	After validation, the cables are placed into a sprue-cutting mechanism; then they are extracted from the machine and sorted

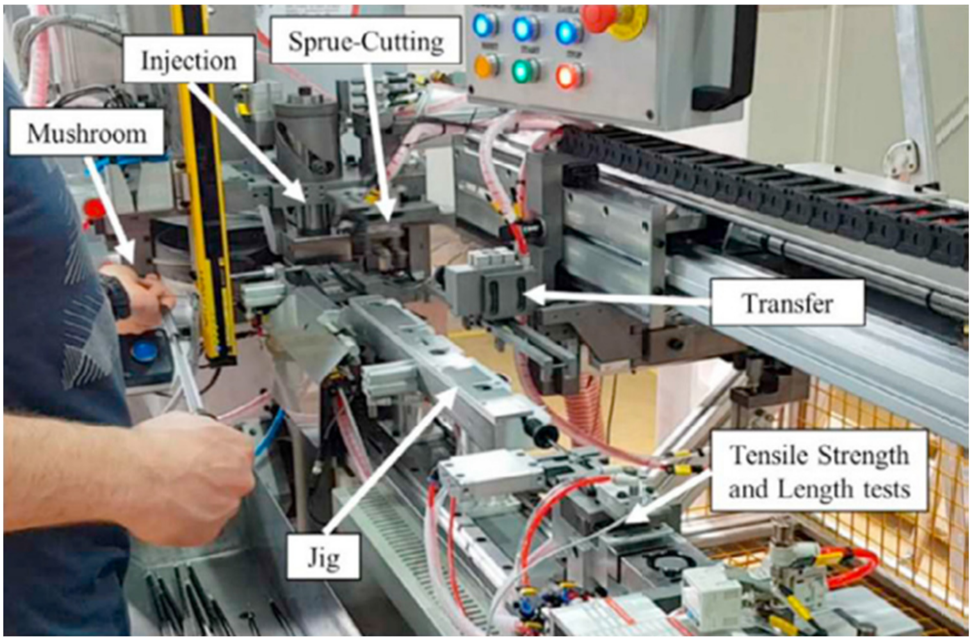

Figure 2. Previously used Bowden-cable production equipment, depicting the various workstations.

Figure 3. Types of Bowden cables produced: (**a**) ZZH, (**b**) IBT, and (**c**) IBT LASSO.

Some of the cable references are coated; this implies the trimming and stripping of these cables before the Zamak terminal injection. These two operations are performed in a separate piece of equipment.

Regarding the cable production process itself, it starts with the sub-product cable + conduit arriving at the equipment (Figure 2), already assembled, trimmed, and stripped (if coated), with the first Zamak terminal already injected. After, an operator picks the sub-product and manually inserts it into the mushroom system; it then passes the cable through the mushroom detection system, conferring its shape. If the mushroom is deemed acceptable, the worker places the cable onto a jig, where the second Zamak terminal injection is performed. Following the injection, the cable is subjected to tensile-strength and length-measurement tests. A transfer system then picks the cable, moving it from the jig to a sprue-cutting mechanism. Finally, the cable is extracted, evaluated, and deemed to be OK or NOK. The cable production can be observed in Figure 4, noting that the focus of this work is the operations necessary for the injection of the second Zamak terminal.

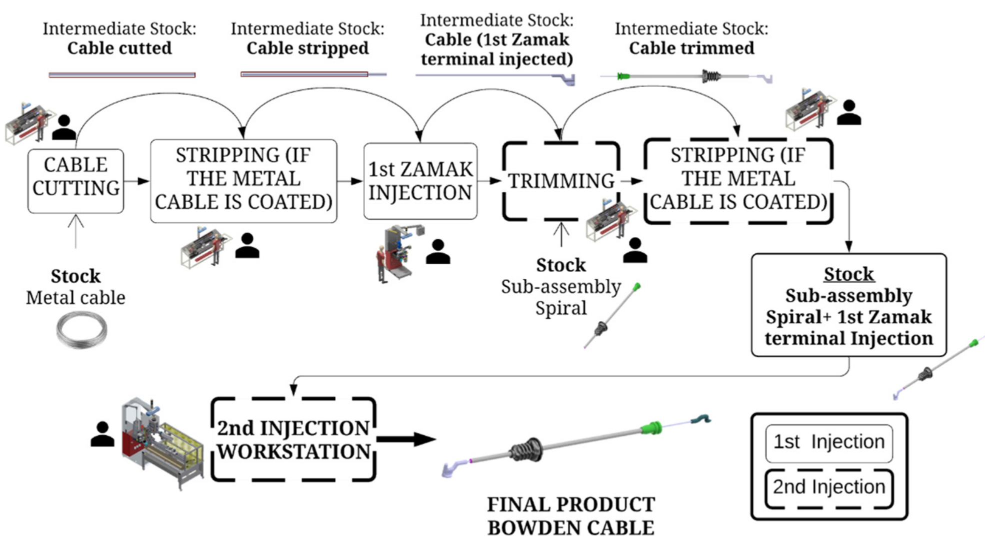

Figure 4. Previously used Bowden-cable production process.

Problem Awareness

When analyzing the concept used for Bowden-cable production, we identified some problems, as follows:

- Regarding the operations required for the second terminal injection, the cables were placed in the mushroom-making system and in the injection system manually;
- There is the need to perform trimming and stripping operations for some cable references, requiring a different piece of equipment that must conduct these operations before the cables being placed into the equipment (Figure 2);
- These additional operations induce the need for more workers, as this new equipment requires an operator;
- Improvement of some of the already existing operations is needed by reducing the occupied space of each of the workstations, as well as improving accessibility for maintenance operations.

It can be noted that the flexibility and productivity of this concept can be improved. To solve these problems, the development of an equipment that would be able to perform all the necessary operations needed before, during, and after the second Zamak terminal injection, in an automated fashion, was proposed.

2.2. Defined Objectives/Requirements

In the present subsection, the various objectives/requirements set for the devised solution are presented:

- Integrate the multiple processes currently separated in multiple equipment in a single piece of equipment, which will automatically manage the evolution of the product along the production line, through an appropriate transfer system;
- Produce three different types of cables—IBT, IBT LASSO, and ZZH;
- The equipment must be highly flexible and agile;
- Develop a more complex transfer system that transports the cable across all necessary operations;
- The operations of executing and detecting the mushroom must be automated;
- Staff requirement—one worker/shift (feeding the system and control);
- Aggregation of cutting and stripping operations in the new equipment, removing employees from the production lines and, essentially, from the logistics and reducing the number of different equipment necessary to the production;
- Validation tests must be performed (mushroom inspection, tensile-strength test, and functional length test);
- Extraction system must collect the cables and separate them into OK or NOK;
- The equipment will need to be robust and reduce as much as possible the vibration effect;
- Protective measures shall be in conformity with Machinery Directive 2006/42/EC;
- Good accessibility for maintenance, servicing, and cleaning activities must be kept in mind;
- The machine cycle time should be less than IBT = 7.5 s/cable, ZZH = 9.5 s/cable, and IBT LASSO = 9.5 s/cable (including workers' manipulation: IBT = 9.5 s/cable, ZZH = 11.5 s/cable, and IBT LASSO = 12.5 s/cable).

2.3. Proposed Concept

As previously mentioned, the proposed concept consists of an equipment capable of performing all the necessary operations required for the second Zamak terminal injection in a fully automated way. In this concept, the only manual task that is required (besides the equipment's control) is the correct positioning of the cable in a jig. These operations are listed below:

1. Cutting/trimming and stripping the cable;
2. Mushroom making;
3. Zamak terminal injection;

4. Sprue-cutting;
5. Tensile-strength and length-measurement tests;
6. Extraction and separation of the cables into OK and NOK.

The initial equipment concept consisted of grouping all the components to perform the necessary operations for the injection of the second terminal, including the trimming/cutting and stripping operations in the equipment. In this early concept, the cables would be moved through by a transfer system above the equipment. However, this transfer system would cause the cables to bend, as seen in Figure 5.

Figure 5. Flexing of a IBT LASSO cable.

Since the correct positioning of the cable in the jig is of high importance to guarantee the quality of the produced cables, this concept was discarded. A new transfer system was devised that would ensure the correct positioning of the cables throughout its production journey. In the following section, the final developed equipment will be presented.

3. Results

In this section, the final equipment design is presented, explaining in detail the most important components of this equipment and their functioning. The designed equipment was developed and implemented; the new production process is shown here, as well as the results obtained from the equipment's implementation, regarding cycle time and cable production. The information presented in this section corresponds to the next two stages of the presented DSR methodology (with the first three being presented in the methods section), these being design and implementation (presentation of the developed equipment and components) and the evaluation step (results of the equipment's implementation).

3.1. Equipment Presentation

As mentioned in the previous section, the newly developed equipment could perform the crucial operations for the injection of the second Zamak terminal in a fully automated way. The overall arrangement of the new equipment and some crucial workstations and systems can be seen in Figure 6. The final solution is an enclosed machine that can perform all necessary operations autonomously, needing only to be fed by the worker (cable with the first terminal already injected and inserted in the spiral). The new design allows the process to be fast and continuous, and, since the cycle-time reduction was a critical requirement, a new transfer system was designed that enables the performance of multiple operations in different workstations, simultaneously.

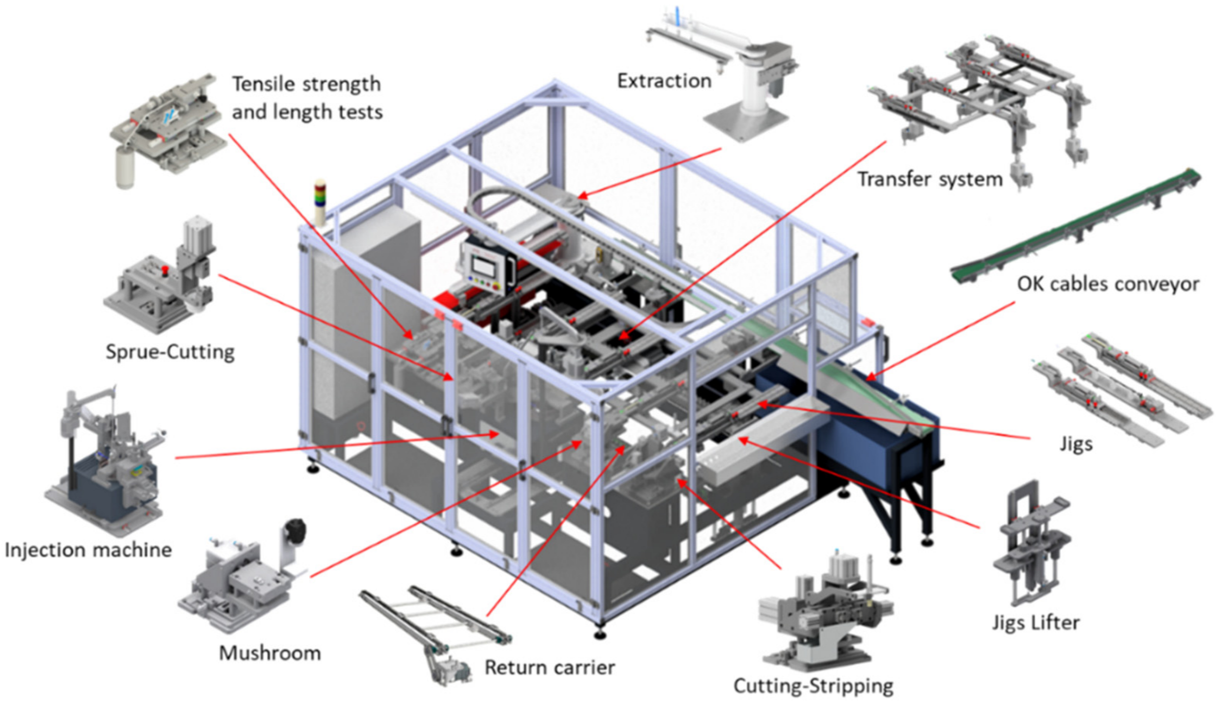

Figure 6. Final developed concept, showing the equipment's main workstations.

3.1.1. Jigs

The jigs have the function of correctly accommodating the cable throughout all the operations, from the start, where the operator positions the cable at the beginning of the line, to the final, where the extraction removes the cable and sorts it. The main components of the jig are the base, and the kit (this being screwed to the base), as observed in Figure 7.

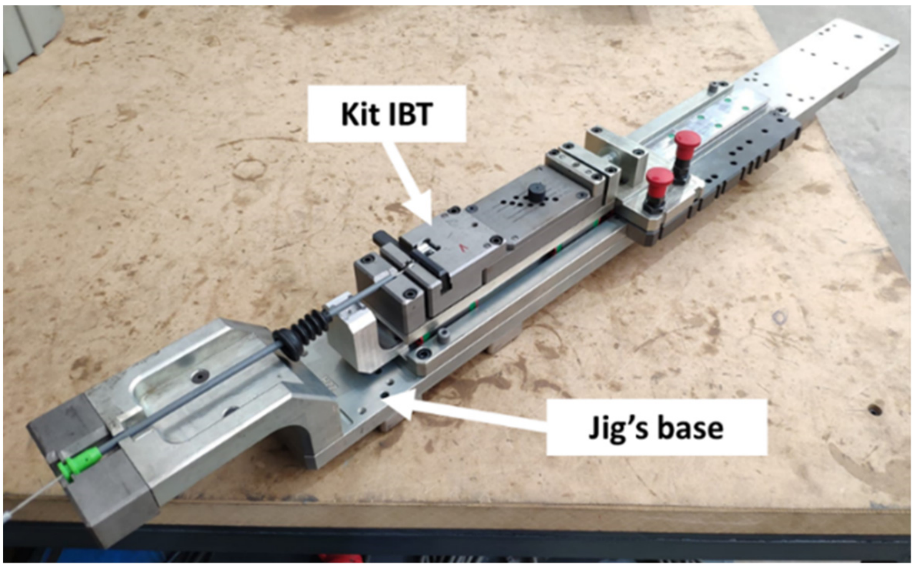

Figure 7. Jig's base and kit (IBT kit) assembly.

The jig's base will remain the same for all the cable references; however, the kits will be specific for each cable type. Three different kits were developed (IBT, IBT LASSO, and ZZH), which are easily interchangeable and adjustable for each cable type and reference. ZZH and IBT LASSO kits can be observed in Figure 8.

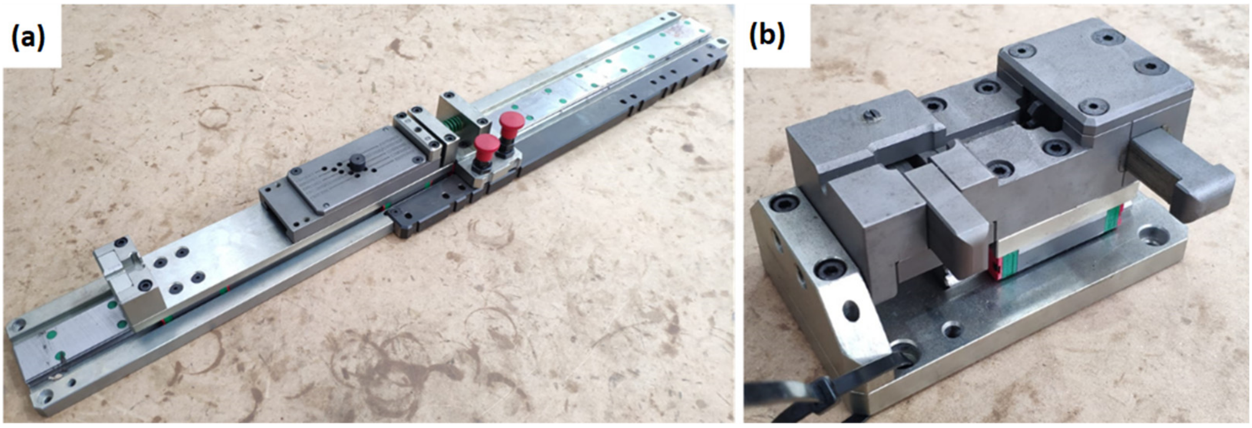

Figure 8. (**a**) ZZH and (**b**) IBT LASSO kits.

To ease the process of changing and adjusting the jigs, marks have been added to the bases of the kits, so its assembly is simpler and faster. These marks can be observed in Figure 9.

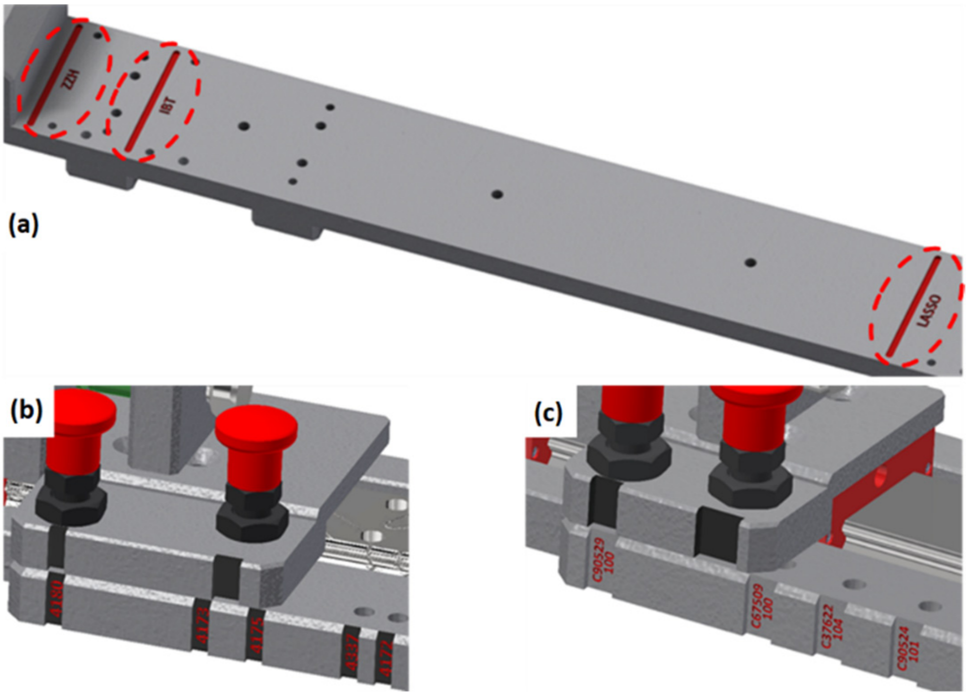

Figure 9. Markings present in the (**a**) base, (**b**) IBT kit, and (**c**) ZZH kit.

3.1.2. Trimming/Cutting and Stripping Workstation

In this newly developed concept, all the operations were aggregated into the same equipment, including the trimming/cutting and stripping of the cables, which were performed in a completely different equipment. An overview of the developed equipment can be seen in Figure 10, showing all the main workstations and some important components, including the trimming/cutting and stripping workstation.

With this concept, two intermediate stocks and associated logistics were eliminated, two machines are no longer needed to perform the trimming/cutting and stripping of the cable, and two workers can be relocated for more productive functions. Moreover, since only a few cable references have a coating, in the last design, the worker needed is just partially working on the stripping station, being constantly relocated whenever needed. In the new design, if a reference with coating is selected for production, the system will operate normally and trim and strip the cable; if a reference without coating is selected, the mechanism will only trim the cable and not strip it.

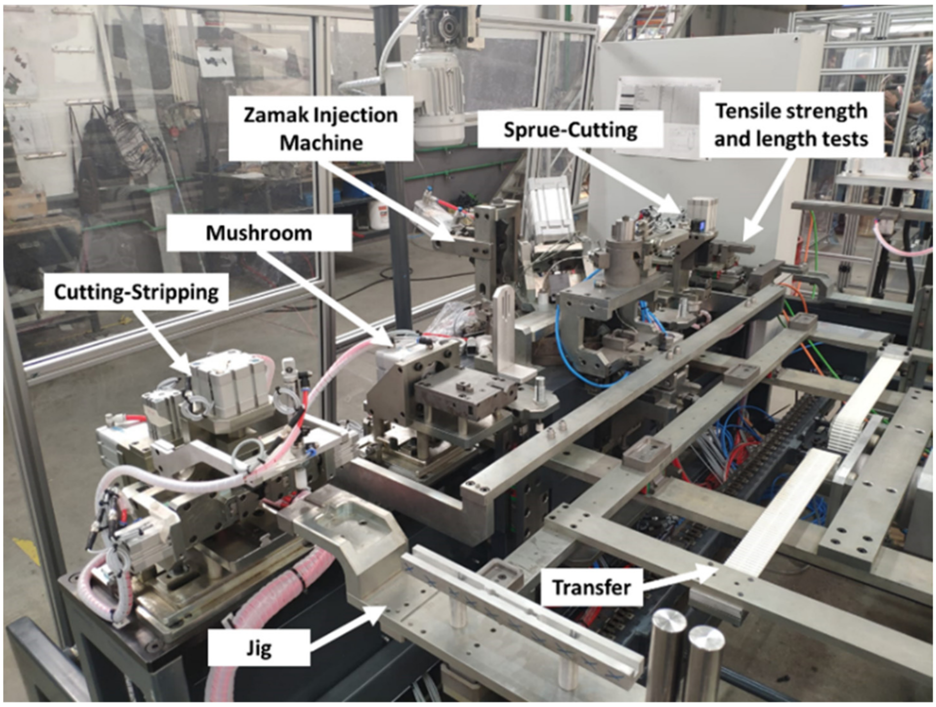

Figure 10. Developed equipment exhibiting the workstations.

This workstation is extremely important, as it is presented as the first workstation where operations will be carried out on the cable. Thus, if any of the actions are not carried out correctly, the subsequent operations are at risk, as well as the quality of the final product. In Figure 11, it is possible to see in detail some components which comprise part of the workstation to better understand its functioning.

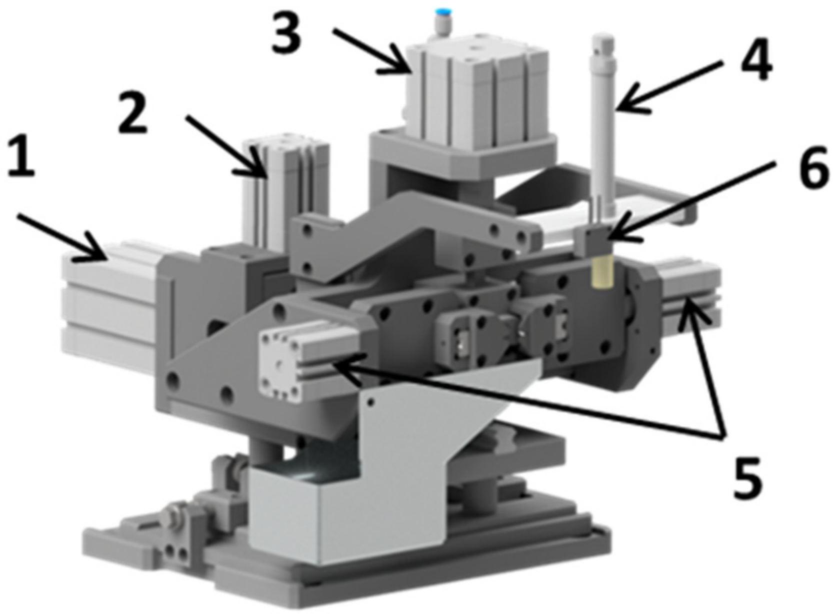

Figure 11. Trimming/cutting and stripping workstation, with the various components numbered (Please see explanation of the numbers in the text).

The station has a movable part that goes forward and backward through the action of a pneumatic cylinder (1) to correctly position the station so that the cable can be cut and stripped. At the beginning, all pneumatic cylinders are retreated.

The cylinder (1) is actuated, pushing the movable part of the station, positioning it correctly so that the cable can be cut, guaranteeing a correct position; otherwise, the cable will have an inadmissible length. After the positioning, cylinder (3) advances, pushing a cutting blade that will trim the cable to the desired dimension.

After the cut, cylinder (2), which contains an associated stop, is actuated, making it descend. In turn, cylinder (1) retreats, causing the movable part of the station to hit the stop on cylinder (2). Since the cable was previously trimmed, the stop will serve as a starting point of the movable part for the stripping operation.

When the movable part hits the stop, the two cylinders (5) with stripping blades will be actuated. Once actuated, cylinder (2) with the associated stop retreats, allowing the movable part to retreat as well (now completely), pulling the coating and, thus, stripping the cable. Cylinder (4) acts as a presser for the cable terminal, ensuring that is correctly positioned during the operations. The system also contains two color sensors (6) which detect the color of the spiral terminal and the spiral itself to prove that the cable reference placed is, in fact, the reference previously selected on the console.

After the trimming/cutting and stripping operations, the cable is transported by the transfer to the mushroom-making workstation.

3.1.3. Mushroom-Making Workstation

When the cable arrives at the mushroom-making workstation (Figure 12a,b), the cable end where the mushroom will be performed is inserted in the mechanism (Figure 12c). Taking into consideration the last design, the necessary steps to obtain the mushroom were performed manually by the worker, who had to hold the cable in place, press a button to activate the system, and pass the cable through the mushroom-detection system. In the new design, all operations are completely automated, so the number of repetitive tasks performed by the worker is reduced, improving product's quality through the reduction of manpower factor, and, more important, protecting the worker's health.

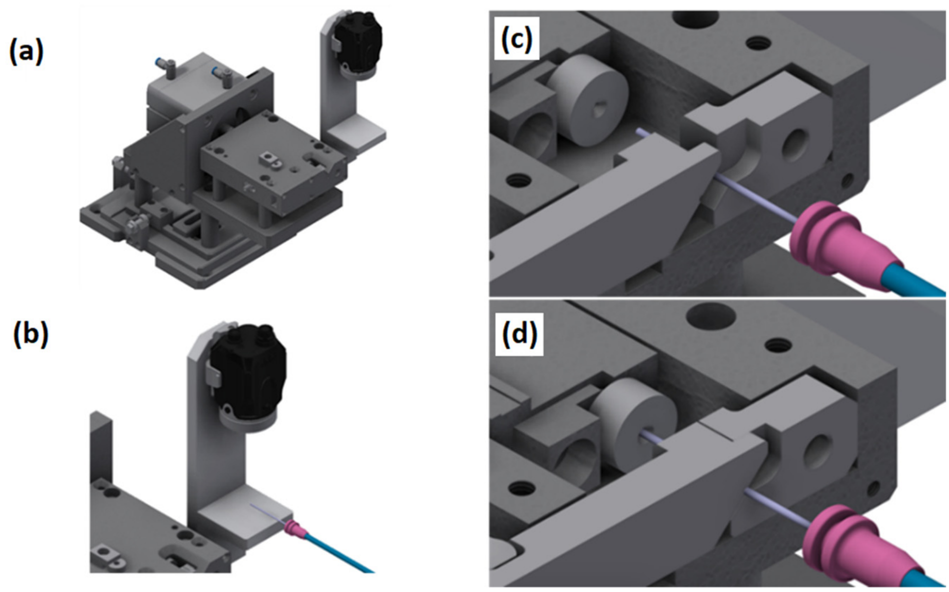

Figure 12. (**a**) Mushroom making workstation, (**b**) detection system, (**c**) mushroom immobilization, and (**d**) mold colliding with the cable tip.

The mushroom is performed when a mold hits the cable tip, thus performing the deformation on the cable end, known as the mushroom. A pneumatic cylinder is actuated, and while the mold is directed to the cable tip, a locking mechanism with two parts closes and immobilizes the cable end (Figure 12c), preventing it from slipping when the mold hits the cable end (Figure 12d). The entire system is driven by the actuation of the pneumatic cylinder.

The detection system was fully changed from a mechanical system that had its problems and limitations to an artificial vision system that will scan the cable end where the mushroom was performed to detect eventual problems.

Furthermore, in the last design, the worker had to remove the cable from the mushroom mechanism and pass it through the detection system before placing it in the next workstation. On the other hand, in the new design, the artificial vision system is placed in a way that, when the cable is being transported to the next workstation, the system can scan the mushroom and detect if the mushroom is OK or NOK, thus saving time and performing an operation when the cable is being transported (Figure 12b). If the system detects any problem with the mushroom, the cable is still transported through all workstations; however, the operations will not be performed, and, at the end of the cycle, the cable will be directed to the NOK cables box.

After the mushroom is performed, the cable advances to the next workstation, the Zamak injection.

3.1.4. Zamak Injection Workstation

The first two operations served to prepare the cable end for the Zamak terminal injection. To get a good result in the injection, the cable end needs to be placed in the injection mold with the mushroom correctly positioned and centered in the mold; otherwise, it can result in a NOK cable. After the proper positioning of the cable, the mold closes, and the injection is performed.

The design of this new concept of equipment provided the opportunity to also implement a new concept for the Zamak injection machine that can help improve the previous workstation's design, mainly by reducing occupied space and improving accessibility for maintenance operations.

The structure that holds in place all the injection-related mechanisms was removed, as well as the control console and the illumination lamp. Furthermore, inside the structure, the previous machine accommodated the electric and the pneumatic boards; the same does not happen in the new design, thus resulting in a much more compact machine compared to the initial design.

Although the machine is a company's standard equipment, to facilitate the maintenance access issues, small improvements were suggested, mainly the fitting of a bearing (Figure 13a) and a linear guideline system (Figure 13b) in the base of the machine. These elements allow the machine to move back and forward in addition to rotate on itself to ease maintenance operations.

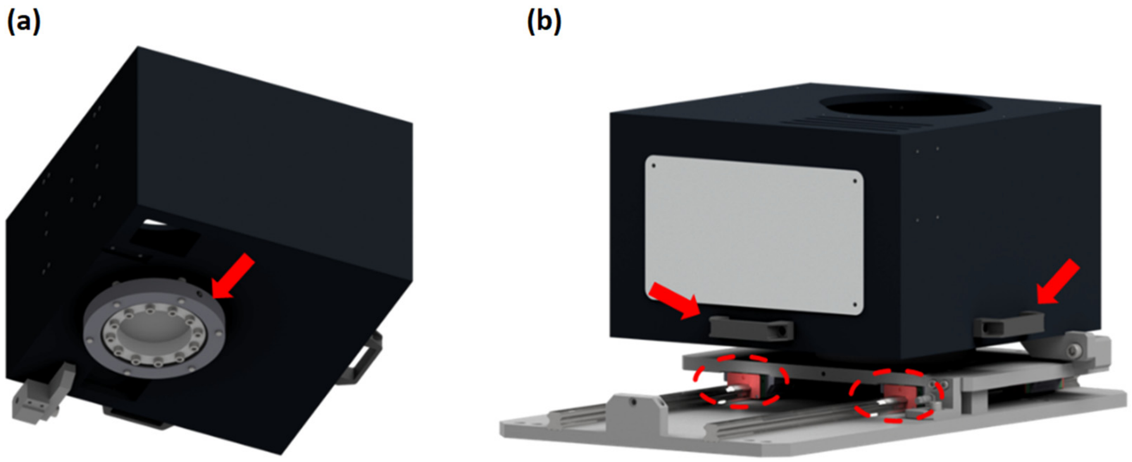

Figure 13. (**a**) Bearing and (**b**) linear guidelines systems installed in the Zamak injection machine.

The new Zamak injection machine installation along with the implemented improvements, allowed to overcome the encountered problems in the initial design, consequently improving this workstation and providing new ideas for other future developments in different machines.

3.1.5. Sprue-Cutting Workstation

After the Zamak injection of the second terminal, the cable is then moved to the sprue-cutting workstation. The main objective of this workstation is to remove the sprue that results from the injection process. The basic functioning of the workstation is the same as that of the last design. A pneumatic cylinder with two associated metallic parts will be actuated to remove the sprue. One of the parts clamps the terminal, while the other removes the sprue.

When the cable reaches this workstation, the cable's Zamak terminal will be positioned onto a base suitable for its shape. As each of the three cable types, IBT, IBT LASSO, and ZZH, have different terminals, three different bases, easily interchangeable, one for each of the three types of cable, were created. These bases will allow the Zamak terminal to sit perfectly when the sprue is being cut, thus avoiding possible defects.

3.1.6. Tensile-Strength and Length-Measurement Tests Workstation

The basic functioning of the tensile-strength and length-measurement tests was unaltered. The first test is the tensile strength, resorting to a pneumatic cylinder and a load cell. Since the loads for the three types of cables produced are different, the air pressure is automatically regulated so that the cylinder can apply the correct and required load for each cable type.

Regarding the length-measurement test, the main components remain the same. The pneumatic cylinder counterweights a 5 kg load; subsequently, the cylinder retreats, and the cable is subject to the action of this load. The load will stretch the cable, and a sensor will be measuring its displacement and check if the cable respects the functional dimensions.

Although the system has the same basic functioning, its design was improved by making it more compact, and the setup time of the workstation was reduced, since now, the only part that needs to be changed is a part that locks the cable terminal in place (Figure 14a).

Another improvement was made with the addition of a system that eliminates possible variations in the positioning of the jigs (Figure 14b). In a simple way, the system makes a measurement of the relative position of the jig upon its arrival at the station, so that the measurement that will be made on the cable is as accurate as possible.

Upon the arrival of the jig at the station, the pneumatic cylinder in the system, which is initially actuated, will recede to a point where the system touches the jig, performing the measurement of the relative position. If the jig is in absolute zero position, the cable length measurement value will be the actual cable length value measured by the station measurement system. However, if the jig is displaced from absolute zero position, in a positive or negative direction, then the new system will measure that same distance and, later, correct the result of the cable length measurement with the relative position value, thus eliminating the difference and obtaining the actual cable dimension value. This system increased the accuracy of cable-length measurements.

In Figure 14c, it is possible to observe the new testing workstation, where the tensile-strength and length-measurements tests are performed. The next step is to extract and separate the cables in OK and NOK.

3.1.7. Extraction and Sorting Workstation

After the cable has passed through all the workstations on the line, it will have to be extracted from the equipment. The cables will also need to be sorted into OK and NOK, and those are the main functions of the extraction system (Figure 15a). Therefore, the system works according to the information collected from the artificial vision system in the mushroom station and from the measurement system on the previous workstation (tensile strength and length measurement). At the tensile-strength and length-measurement station, the system collects the cable from the jig (Figure 15b), and, if the system has the information that the cable is NOK, then the mechanism will deposit the cable directly in the NOK cable box (Figure 15c), since its normal functioning is at stake.

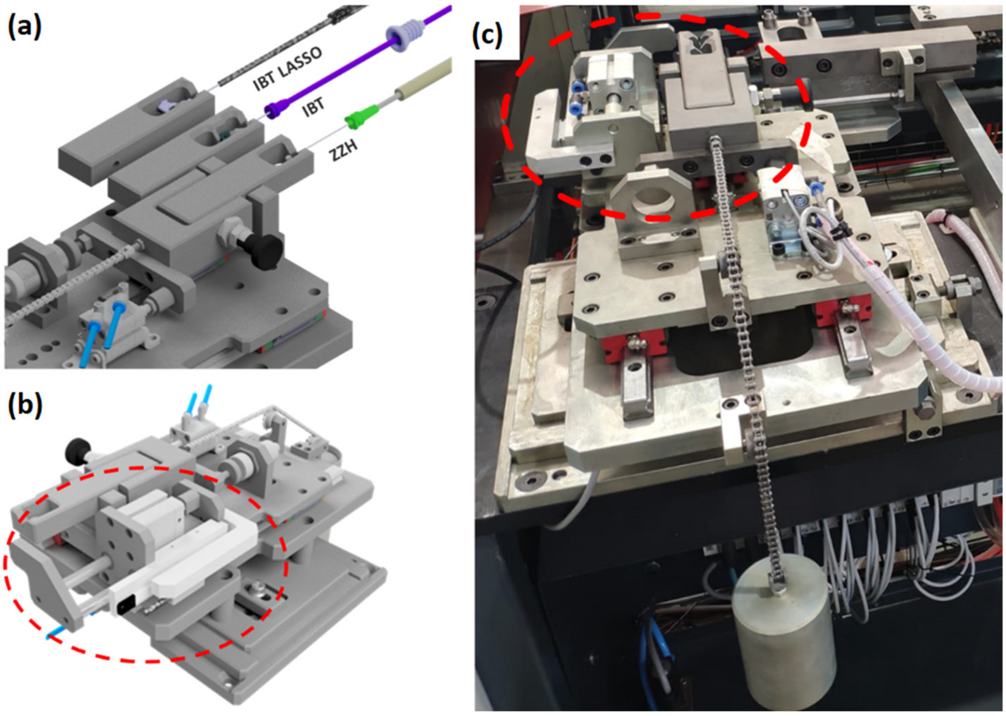

Figure 14. (**a**) Interchangeable cable-measurement component, (**b**) positioning-correction system, and (**c**) complete testing workstation.

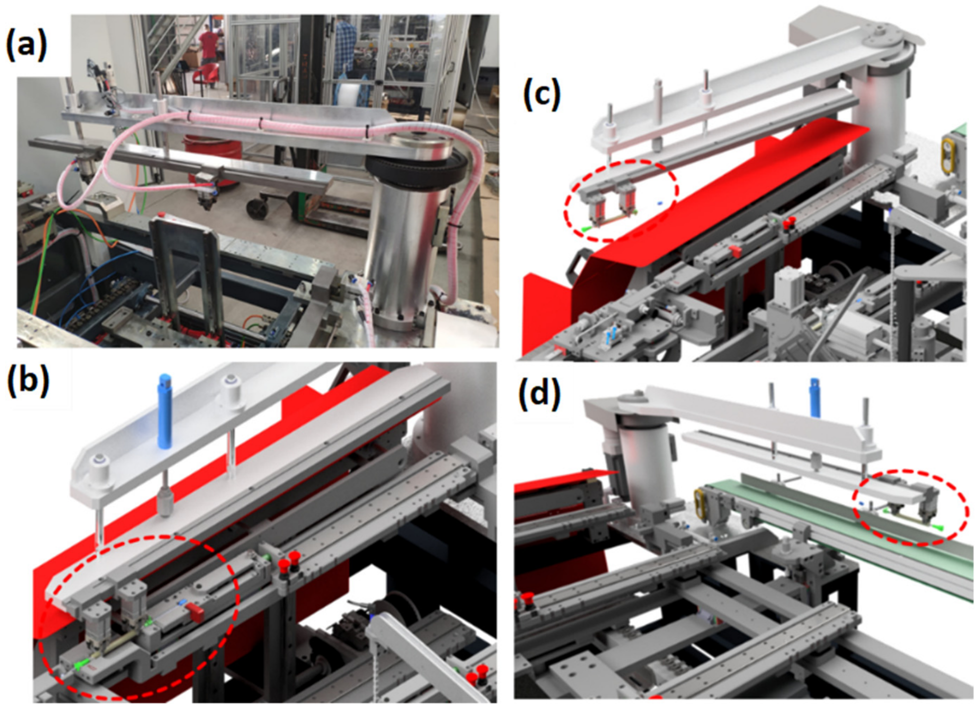

Figure 15. (**a**) Extraction and sorting workstation, (**b**) Bowden cable being collected, (**c**) cable being placed into a NOK box, and (**d**) cable being transported and placed into the OK box.

In Figure 15b, it is possible to observe the system collecting the cable from the jig; the first step is the actuation of the cylinder. This cylinder promotes the descent of a system that contains two pneumatic cylinders with claws that will carry the cable. The system is guided by using two shafts to prevent oscillations in the vertical movements. Subsequently, the first cylinder retracts, and the system will rotate, using the servomotor. If the cable is NOK, the system performs a clockwise rotation, and the cable is deposited into the NOK box (Figure 15c). If the cable is OK, the system rotates counterclockwise and releases the cable on the conveyor to be transported to the OK cables box (Figure 15d). Details about this can also be seen in Figure 16.

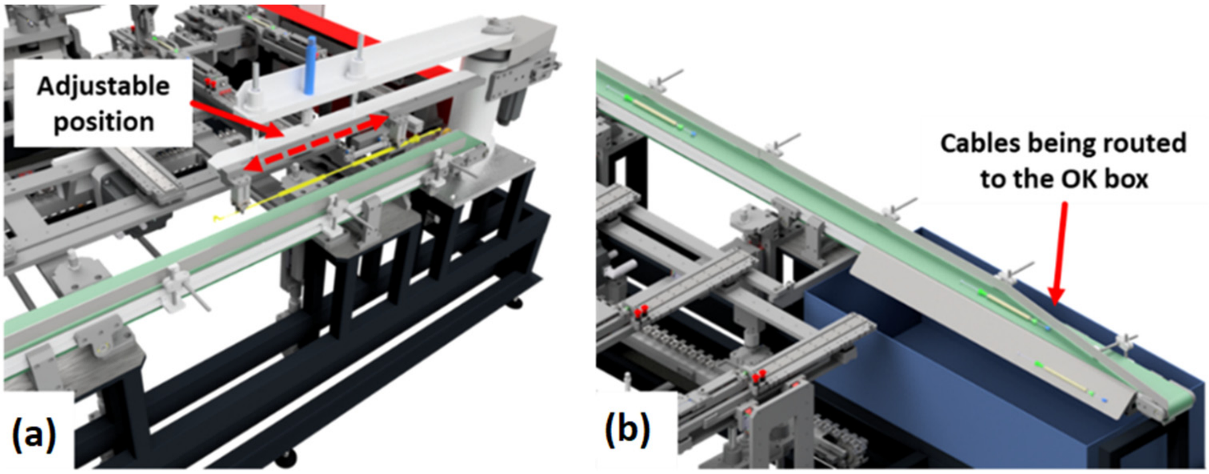

Figure 16. (**a**) Adjustable position of the pneumatic cylinders that carry the cable. (**b**) Cables being routed to the OK box.

It should be noted that the claws that carry the cable allow adjustment in relation to their positions (Figure 16a), thus allowing them to carry all cable references, from the shortest to the longest. At the end of the conveyor, the cables are automatically routed to the OK cables box (Figure 16b).

The conveyor is needed because the worker's normal operating position is located on the opposite side to the extraction. In this circumstance, the worker would not have much control over the number of produced OK cables and would have to travel to the opposite side of the equipment to change the OK box when it is full. Using the conveyor, OK cables are deposited near the worker's workstation, thus increasing the worker's control over the production process and providing easier access.

3.1.8. Transfer System

The transfer system's main function is the transport of the sets jig + cable from the beginning of the process, when the cable is placed in the jig by the worker, until the end, when the cable is extracted and sorted into OK or NOK boxes.

The system's movement involves two main movements—vertical and horizontal (Figure 17a). When the operations on the cable are over, at first, the jigs (with the cables) will be raised from their working position, and then a horizontal movement toward the next station is performed. When the jig arrives at the next station, the transfer will lower it to perfectly place it in the working position.

When the jigs are in their working position, they are supported and kept in place by two support bars, one in front of the jig and the other in the back (Figure 17b,c). When in transport, the transfer has support parts (also in the front and back of the jig), where the jig fits perfectly and stays locked until it is lowered and placed in the support bars. With the jig in place, the transfer system retreats to start another transport.

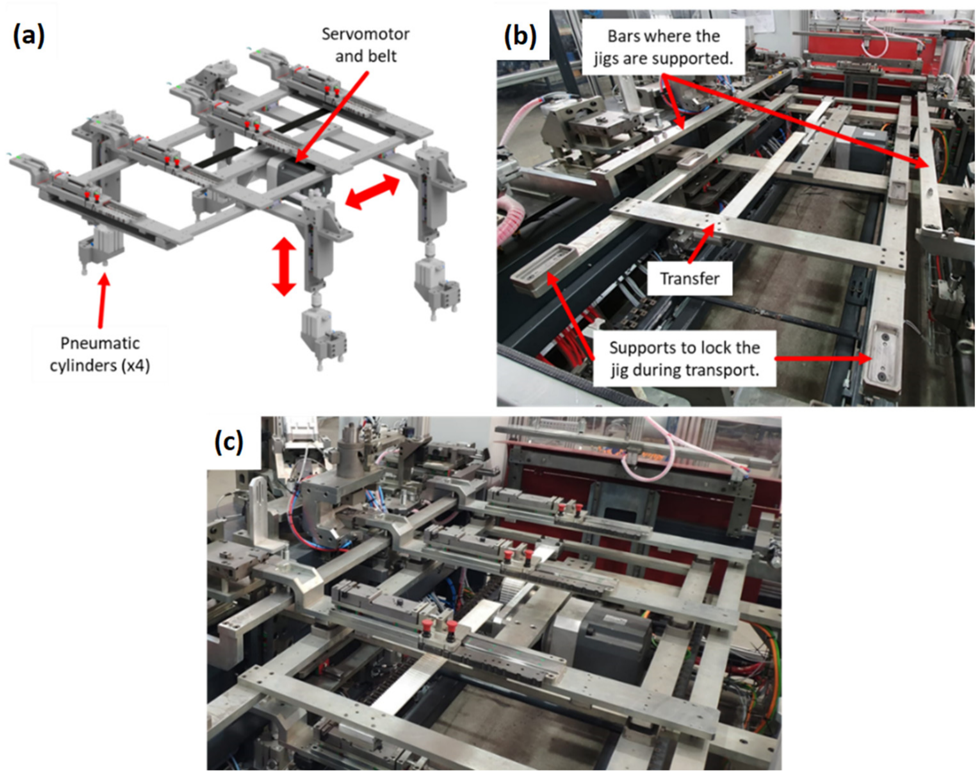

Figure 17. (**a**) Movements performed by the transfer system, (**b**) support bars for the equipment's jigs, and (**c**) jigs mounted onto the support bars.

The up/down movement is performed, recurring to four pneumatic cylinders that elevate and descend the transfer system's structure and the jigs when required. The forward/backward movement is executed by the servomotor and belt, coupled to the transfer. The structure is equipped with linear guideline systems that allow the parts to move, whether up/down or forward/backward, during the transport.

The development of this new and innovative transfer system for the product's transport across workstations in the machine allowed for an increase of operations being performed simultaneously, allowing an improvement in the machine's cycle time. It also gave the possibility to aggregate more operations in one piece of equipment, since it can easily transport the cables and jigs across the various workstations. Integrating operations in the same equipment is an effective way to maintain a continuous workflow, while reducing intermediate stocks and logistics.

3.1.9. Return Carrier

The return carrier has the function of transporting the jigs from the end of the line to the beginning, so that it is possible to start a new cycle (Figure 18). It has a simple way of functioning. A servomotor powers two chains, parallel to each other, where the jigs are coupled. Through the chain movement, the jigs are transported.

Similar to the transfer system (Figure 17b), the return carrier also has support parts that lock the jig during the transport (Figure 18a). In Figure 18b, it is possible to observe a jig that is locked and is being transported to the machine's start by the return carrier. The system is bolted to the machine's metallic structure in several points on each side, and its positioning can be adjusted. The servomotor is also bolted to the structure.

The return carrier has great importance for the operation of the equipment, since it allows for a continuous and uninterrupted workflow. It makes the jigs with the cable already extracted reusable, making them return to the beginning of the cycle, where a new cable to be worked can be inserted by the worker.

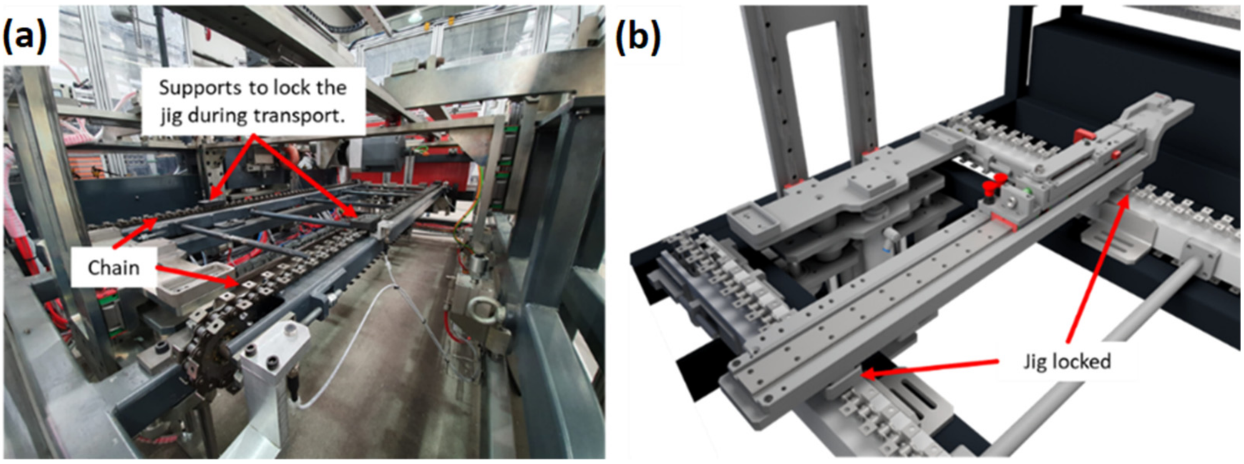

Figure 18. (**a**) Return carrier and (**b**) jig being moved within the equipment.

3.1.10. Jig Lifter

The jig lifter (Figure 19) has the function of raising the jigs from the return carrier until they are collected by the transfer at the start of the cycle, as well as at the end of the cycle, to lower the same jig from the transfer to the return carrier, so that it is transported again to the beginning of the line. In this way, the equipment has two lifters, one at the beginning and one at the end of the line.

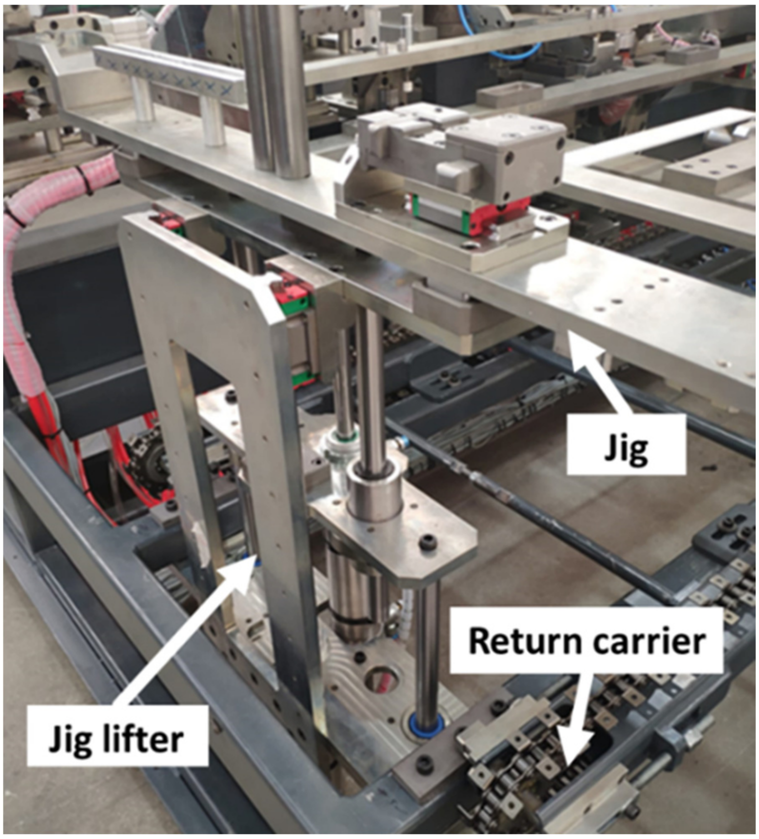

Figure 19. Jig lifter.

The lifter has two pneumatic cylinders that will raise/descend the jig. The first cylinder is actuated, raising the jig, allowing it to unlock from the return carrier. Then the second cylinder is actuated, further elevating the jig, placing it higher than the transfer, thus allowing the jig to be collected and supported on the transfer system. Regarding the second lifter, at the end of the line, the concept is the same. When the transfer retreats to start another transport and to pick the jig on the first lifter, then the two cylinders will be actuated, one at a time, and will pick up the jig. After picking up the jig, the cylinders will retreat, descending the jig to the return carrier. Both lifters have four shafts and a system of linear guidelines for each one. These components allow the system to be more robust and prevent high oscillations during transport that could compromise the jig's positioning on the transfer system or on the return carrier.

3.2. New Production Process

With the development of this new equipment, the production process was improved, especially by aggregating all the necessary operations for the second Zamak terminal injection into a single fully automated piece of equipment. The new production process can be observed in Figure 20.

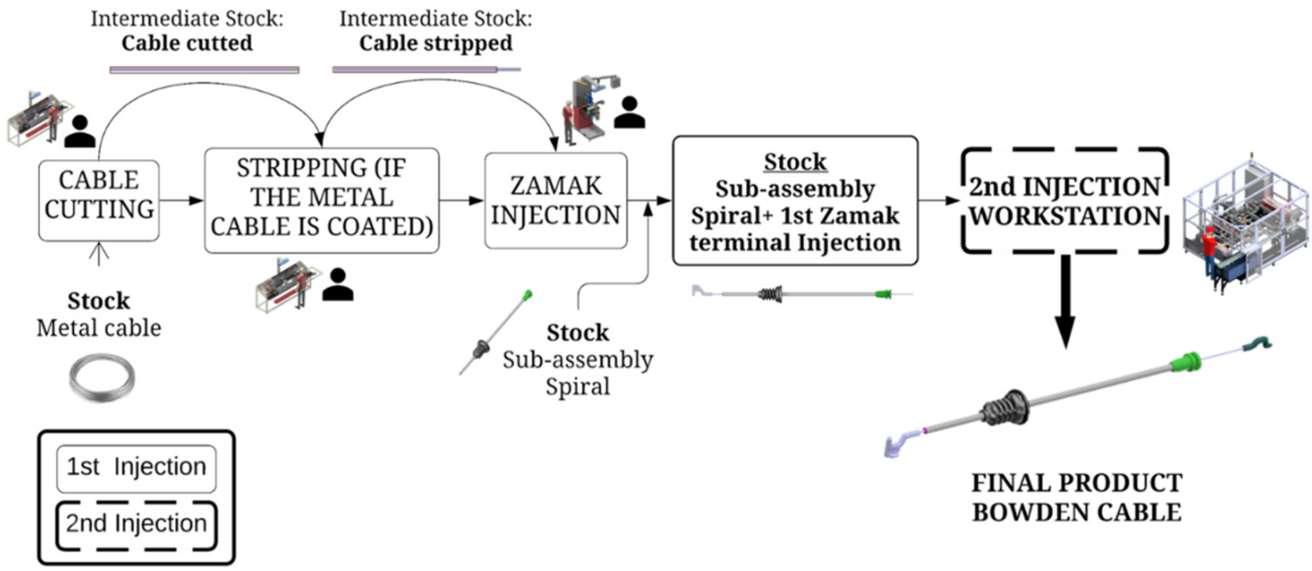

Figure 20. Developed and improved process to produce Bowden cables.

The main advantage of the new process is to reconcile all the processes necessary to produce a Bowden cable in a single equipment, allowing a much easier management, avoiding inventories and intermediate controls, and ensuring a uniform quality of the products, removing the variability introduced by the human factor. A more detailed comparison of this process with the previously implemented one is presented in Section 4.

3.3. Implementation Results

The developed equipment was implemented and tested in the production of Bowden cables. With many improvements made to the equipment, we were able to achieve a reduction in cycle time and an increase in process productivity. The average cycle time values were determined for the previous and new equipment, as well as their cable production per hour, and these values are presented and compared in Table 3. The cycle time is the main key performance indicator of this process, as this parameter influences the overall component production. Furthermore, its evaluation can be made in a shorter period of time (as compared to improvements regarding logistics or maintenance operations).

Indeed, a reduction of the production cycle time of 25% was achieved, inducing an increase of 30% in the production of Bowden cables per hour. The average selling price of a Bowden cable is roughly 0.50 €; this implies that, by using the newly developed concept, there is an increase in annual revenue of 201,500 € when compared to the previous concept.

Table 3. Comparison of the cycle time and production of cables per hour of the previous and new equipment.

	Previous Concept	New Concept	Percentage Deviation
Cycle time (s)	12.5	9.5	−25%
Production (cables/hour)	288	378	+30%

4. Discussion and Conclusions

The developed equipment was designed as an improvement for a previously used Bowden cable production process, using the DSR methodology. The present section corresponds to the last stage of the proposed methodology (Conclusion), where the final process is evaluated and compared to the previous one, drawing the final conclusions regarding the equipment's development. Similar to the work presented in Reference [40], this equipment aims at improving the productivity and flexibility of the cable production process by solving problems found on the previously used equipment, as well as identifying and devising improvements for the process, as seen in Reference [42]. The developed and implemented concept highlights the benefits of proper use of automation to increase process productivity and reduce cycle times, as reported by other authors' works [41,43], as a viable alternative to more expensive robotic applications, as well as the benefits that arise from the proper use of a methodology that can serve as a framework to improve manufacturing processes by performing a proper process study and problem identification, developing solutions, and then testing them (iterating if needed) to obtain the best possible solution (for the analyzed case).

The newly developed equipment can perform all needed operations for the injection of the second Zamak terminal.

- Cutting/trimming and stripping the cable;
- Mushroom making;
- Zamak terminal injection;
- Sprue-cutting;
- Tensile-strength and length-measurement tests;
- Extraction and separation of the cables into OK and NOK.

The developed process brings many important advantages over the previously employed process, such as the following:

- Two intermediate stocks and associated logistics are eliminated;
- Trimming and stripping operations are integrated into the new equipment:
- Manpower factor is reduced (production and logistics);
- Process flow and work management are improved;
- Single maintenance operation instead of several;
- Increase of the level of automation of the whole process and subsequent reduction of manual operations/repetitive tasks.

Significant improvements were made to the previous concept, both in terms of process improvement, registering cycle time reductions of 25%, and a subsequent productivity increase of 30%, while also optimizing the equipment occupied space and improving accessibility for maintenance operations. However, regarding the improvement of maintenance operations, this could not be characterized in full, due to the equipment's short implementation time (requires a longer period of evaluation to assess this improvement). Moreover, the internal logistics previously needed to transfer the semi-products from workstation to workstation, was completely unnecessary in the current context. However, the operations of feeding components to feed the novel equipment remain needed. Thus, it can be inferred that about 55% of the time previously spent in internal logistics around the equipment now developed was cut. This cannot be referred to as a key performance indicator, but it is a good achievement regarding the indirect costs involving the process. All the requisites established at the beginning of the project were met by the newly developed concept.

Furthermore, there is a reduction of required manpower, as well as an improvement regarding occupied space and maintenance accessibility (a comparison between the two processes can be made by analyzing Figures 4 and 20, referring to the old and new injection process, respectively).

The use of the DSR methodology brings many advantages to these types of studies, focused on the improvement of already existing processes. In the presented study, the use of DSR produced very satisfactory results. This is achieved through the careful study of the currently implemented process, developing solutions based on the user's insight of the process, as well as providing a framework for process and equipment design and improvement, that can be applied to a wide multitude of case studies, including different manufacturing processes. This differs from the design and improvement process of what is usually made for these studies, where the prerequisites are somewhat defined by the manufacturing companies (who seek process-improvement solutions to manufacturing problems) and are conditioned by the existing means immediately available [24,38,39]. However, there are some limitations regarding the use of this methodology, such as the following: it is most suited to already existing processes, focusing on their improvement and problem identification; it requires a careful analysis of the initial process, being subject to the final decision of the analyzing team; and it also may require multiple iterations, making it a time-consuming method in some of the implemented cases.

In addition to the shown framework that can be used to solve manufacturing problems and improve these types of processes, a set of new mechanical and automatic concepts were developed that can be useful for other applications, being an important piece of work to be considered as transferrable knowledge and contributing by this way to the improvement of other equipment through the application of these concepts tailored to different needs. Thus, this work not only highlights the relevance and importance of the use of automation in manufacturing processes, particularly in the automotive industry, but also shows the benefits of the implementation of a framework for designing and improving processes, based on careful process analysis and problem assessment, such as the DSR. As previously mentioned, the use of this methodology for the improvement of these types of cases has shown itself to be quite beneficial, with high potential to be applied to a wide variety of manufacturing processes.

Author Contributions: N.M., investigation, main research and data collection, and writing—methodology; F.J.G.d.S., conceptualization, methodology, investigation, supervision, writing—reviewing; R.D.S.G.C., supervision, visualization, and resources; A.G.P., visualization, data curation, writing—reviewing; L.P.F., formal analysis, data curation, and resources; V.F.C.S., formal analysis, visualization, and writing—draft and reviewing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding, and the authors did not receive any funding regarding the development of this work.

Data Availability Statement: Not applicable.

Acknowledgments: The Authors want to thank Mário Cardoso for the data provided, as well as the availability to supervise M.Sc. students from ISEP to carry out their master's thesis.

Conflicts of Interest: Authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper. Moreover, the authors declare no conflict of interest.

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