



Article



# Automation of Post-Injection Gate Handling in Automotive Polymer Moulding: A Design Science Research Approach

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**Abstract:** Polymer injection moulding is a vital manufacturing process in the automotive industry, where high production volumes, strict quality requirements, and short cycle times impose increasing demands on automation and process reliability. In cold-runner injection systems, the formation of polymeric gates is unavoidable, and their removal often represents a process bottleneck, which frequently requires manual intervention or complex retrofitted solutions, thus limiting productivity and introducing safety, ergonomic, and economic concerns. This paper presents the design, implementation, and industrial validation of an automated transport system dedicated to the removal of polymeric gates generated during the injection moulding of spiral terminals for automotive control cables. The proposed solution enables the extraction of the gate from the lower mould without obstructing the injection zone or requiring structural modifications to the production line. Industrial implementation demonstrated that the automated solution effectively restores continuous operation of the assembly line, enhances process reliability, and reduces operator workload and exposure to repetitive tasks. An economic assessment revealed a return on investment (ROI) of approximately 22 working days, highlighting the strong economic viability of the proposed approach. The system can deliver substantial productivity gains while maintaining low implementation complexity.

**Keywords:** polymer injection moulding; automated gate removal; industrial automation; automotive control cables; process integration

## 1. Introduction

The automotive industry is a critical driver of the global economy, significantly contributing through job creation, resource utilization, and advancements in technical and technological domains [1]. Within this industry, the automotive components sector holds prominence, with control cables playing an important role in vehicle functionality. These cables facilitate essential operations, such as opening doors, activating the handbrake, and controlling the accelerator [2]. Efficient production processes for control cables are imperative to meet the high-volume demands of the automotive industry while maintaining cost-effectiveness. At their core, they consist of a metallic cable that is progressively enclosed by several protective and functional layers, each with a specific function [3]. The innermost layer is a polymer inner sheath, typically produced by extrusion, whose primary function is to reduce friction between the metal cable and the surrounding structure, called spiral. This sheath reduces sliding resistance, thus contributing to smoother operation, reduced wear, and increased service life of the



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cable system [4]. The inner sheath is surrounded by a helically wound steel spiral, which provides the necessary mechanical stiffness and structural integrity to the cable assembly. This spiral ensures dimensional stability, guides the movement of the inner cable, and allows the system to withstand compressive and bending loads during operation [5]. The outermost layer is an external sheath, commonly manufactured from thermoplastic materials such as polyvinyl chloride (PVC) or low-density polyethylene (LDPE), which protects the internal components from environmental exposure. To integrate the control cable into the vehicle structure, spiral terminals are over moulded onto the outer sheath using polymer injection moulding processes. These terminals ensure accurate positioning of the cable set and secure its fixation to the vehicle [6]. At the extremities of the metal cable, end fittings are formed to guarantee reliable mechanical attachment. These terminals are typically produced through a combination of plastic deformation, often referred to as mushrooming, followed by Zamak die casting, resulting in robust and durable connections capable of sustaining repeated operational loads. Research in this area has focused on optimizing the injection process to enhance efficiency. Under the scope of control cable design, Pereira et al. [7] proposed a new injection die geometry to reduce the Zamak gate mass of the metal cable terminals, significantly reducing waste in the injection process. Under a different scope, Sousa et al. [8] improved the Zamak nozzle heating process through geometrical modification of its shape, which led to improved safety and less maintenance interventions.

Irrespective of the gate type, Zamak or polymeric, post-injection separation it is required to break the gate from the injected parts. The most simple solution of manual breaking requires allocating a dedicated worker to a repetitive task, possibly leading to health issues such as tendonitis, and affects productivity and consistency of the task [9]. Automation offers a viable alternative, and the procedure becomes more efficient, since the equipment will transport, cut, separate gate and part, and redirect both to different containers. Automated systems reduce cycle times, enhance safety, and eliminate operator health risks, though they require substantial initial investments and may lead to workforce reallocation [10]. Despite these challenges, automation provides significant advantages, including cost reduction, improved product quality, and competitive positioning in the automotive industry [11]. Innovative approaches to automation continue to emerge, with a focus on modularity, adaptability, and integration. For example, incorporating advanced robotics and Internet of Things (IoT)-enabled systems could further enhance precision and flexibility, enabling real-time monitoring and predictive maintenance [12]. As automation technologies evolve, their application in automotive manufacturing will likely extend beyond efficiency gains to include sustainability, energy optimization, and workforce upskilling [13].

Several studies demonstrated the transformative impact of automation on automotive manufacturing [14,15]. Tizilov et al. [16] designed a robotic assembly segment to produce passenger vehicle body structures through numerical simulation of manufacturing operations performed by industrial robotic systems. The authors established an operational cyclogram for the assembly station and allocated welding spots among the robots, considering constraints such as cycle time, body-in-white geometry, safety requirements, workspace accessibility, electrode configuration, and the clamping force applied by the welding gun at each joint. The simulation outputs provided a validated digital model that supported the subsequent installation phase on the shop floor. Moreover, the development of control algorithms, service routines, auxiliary programs, and optimized robot trajectories contributed to minimizing commissioning time and associated implementation costs. Stepanić et al. [17] implemented a networked production architecture in which data acquisition, communication, and processing were used for process optimization in the automotive industry. Within this scope, a robotic assembly solution was developed and applied to the automotive sector, in which smart sensors were integrated directly into the robotic system to enhance positioning accuracy and operational consistency during component assembly. The sensor-driven feedback enabled more precise handling and alignment of parts, while the real-time communication between system elements significantly reduced the occurrence of assembly errors. The results demonstrated major improvements in assembly precision and reliability. Using CATIA V5 software, Naveen and Vishwanatha [18] designed an automatic system as an alternative to a manual assembly process of a pin/bearing assembly for a gearbox cover housing. The system was pneumatically driven and involved three movements: gripping, aligning, and inserting. A virtual replica of the equipment was constructed, which enabled proposing design improvements to the real system, ultimately leading to smaller cycle times, fewer errors, increased repeatability by minimizing human intervention, and less scrap. Quantification of the system benefits was left to future construction of a prototype and field measurement. Fleischer et al. [19] addressed automating the production of micro actuation devices, namely 1.4 mm diameter spur gears to be fabricated using powder injection moulding. The fabrication operations were divided into individual tasks able to benefit from automation: mould opening and part extraction, handling, and transportation. Challenges arose due to the small scale of the components, requiring extremely high movement precision in the micrometre range, as well as low tension in the transported components, in the milli-newton range. The study highlighted the necessity of automating the transport process to enable medium and large-scale production,

ensuring both economic feasibility and quality control of the produced gears. Ribeiro et al. [20] automated several manufacturing steps of control cables to improve lubrication of the inner tubes that contact with the spiral. Previously, the process was slow and required lengthy production stops. A quick-change reservoir system was implemented, allowing the reservoir to be removed, refilled, and reinstalled efficiently. Additionally, an automated mechanism was introduced to detect cables with insufficient lubrication caused by poor injection. The proposed improvements highly increased throughput of the lubricant injection lines by reducing downtime and achieved a 70% reduction in lubricant usage, directly lowering process costs and environmental impact. Pinto et al. [21] investigated the injection moulding process of Zamak control cable terminals, with emphasis on the post-injection separation of the moulded components from the feeding system. The authors developed an automated pneumatic system capable of separating Zamak control cable terminals from the associated gates under stringent spatial constraints. By introducing automation into a previously manual stage of the process, the system achieved a substantial reduction in production time, with reported 39% improvements, thereby enhancing overall manufacturing efficiency. The study was structured according to the Design Science Research (DSR) methodology, ensuring a systematic link between problem identification, solution development, and industrial validation.

This study focuses on the design and implementation, on an industrial automotive components company, of an automated transport solution intended to overcome the operational limitations associated with polymeric gate removal in injection moulding processes used for automotive control cable production. A compact and reliable system is developed that performs gate removal without encroaching upon the injection area or necessitating structural modifications to the existing moulding equipment or surrounding assembly line. The proposed solution shall accommodate severe spatial constraints typical of industrial environments, while enabling rapid installation and straightforward adjustment through a modular mechanical architecture. This modularity allows fine positional tuning of the gripping and transport elements, facilitating adaptation to process variability and potential future applications.

## 2. Methods

### 2.1. Methodology

The DSR methodology was employed in this study, aiming at innovative solutions grounded in theoretical foundations and validated through practical application. This approach is particularly well-suited to advance existing processes and machinery, address real-world challenges, and contribute to both technical and scientific advancements. As such, DSR is commonly adopted in fields like engineering and computer science [22]. Its systematic framework perfectly aligns with the objectives of this work, which involves the development of novel solutions to address limitations in an existing machine. The DSR methodology is based on the application of six key stages [23,24]:

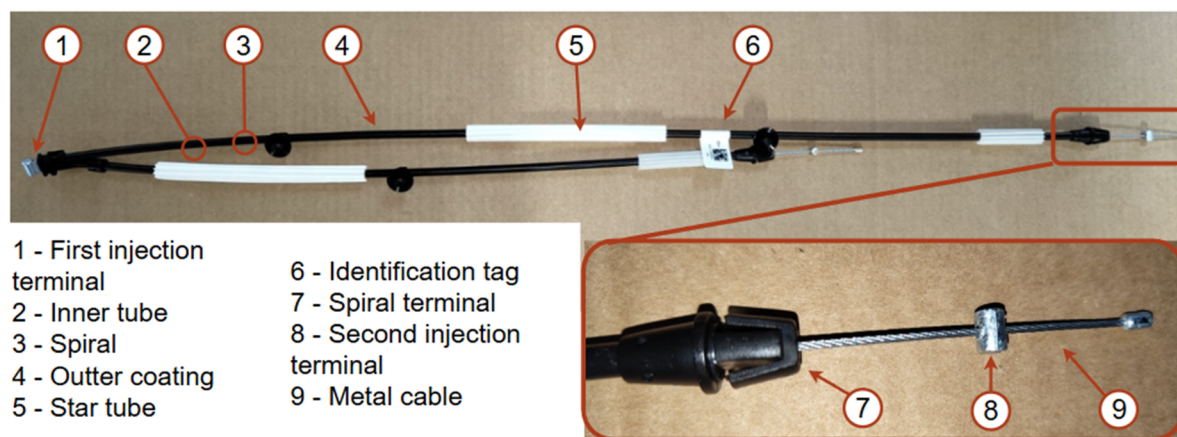
- **Problem identification:** The first stage consists of a detailed examination of the existing machine, production system, or manufacturing process to identify functional deficiencies, operational constraints, and sources of inefficiency. This analysis extends beyond the immediate symptoms of the problem by including root causes, boundary conditions, and potential opportunities for technological improvement. Particular attention is given to process interruptions, spatial constraints, integration limitations, and human-machine interaction issues that may affect productivity and reliability;
- **Objectives:** Considering the information gathered in the initial analysis, the second stage focuses on defining clear and measurable objectives for the proposed solution. At this point, the functional requirements, performance targets, and operational constraints are formalized. Considerations such as available installation space, compatibility with existing equipment, technological feasibility, cost limitations, production rate, and expected implementation timelines are taken into account to ensure that the defined objectives are realistic and aligned with the company needs;
- **Design and development:** The third stage encompasses the conceptualization and development of the proposed solution. This phase involves translating the defined objectives into a real equipment by means of mechanical design, component selection, system integration, and, where applicable, control strategy definition. Design decisions are refined by an iterative process to balance functionality, simplicity, robustness, and ease of integration, aiming to propose a solution that is suitable for industrial deployment;
- **Demonstration:** In the fourth stage, the developed equipment is installed in its intended operational environment to demonstrate its feasibility and functional performance. The solution is integrated into the target machine or production line, allowing its behaviour to be observed under real operating conditions. This stage verifies that the system performs its intended functions and interacts correctly with existing equipment and processes;

- Evaluation: The fifth stage involves a systematic evaluation of the implemented solution, focusing on its ability to meet the earlier defined objectives. Performance indicators such as reliability, operational efficiency, impact on production flow, and ease of use, are assessed. Any deviations from expected behaviour or unforeseen effects are carefully analysed to identify their causes, and should lead to refinements to the design and insights of the solution limitations and robustness;
- Conclusions: Finally, the sixth stage is dedicated to consolidating and communicating the results of the research. This stage includes comparing the initial problem state with the outcomes achieved after implementation, assessing the effectiveness of the proposed solution, and documenting the technical and methodological knowledge generated throughout the process.

In this paper, the application of the DSR methodology begins in Section 2.3, where the first stage is addressed following an overview of the manufacturing process and injected components given in Section 2.2. The definition of objectives and requirements corresponding to the second stage is presented in Section 2.4. The design and development activities associated with the third stage are detailed in Section 3.1, while the demonstration and evaluation stages are discussed in Section 3.2 through dedicated subsections. The final stage, which synthesizes the findings and insights obtained from the entire study, is presented in Section 4.

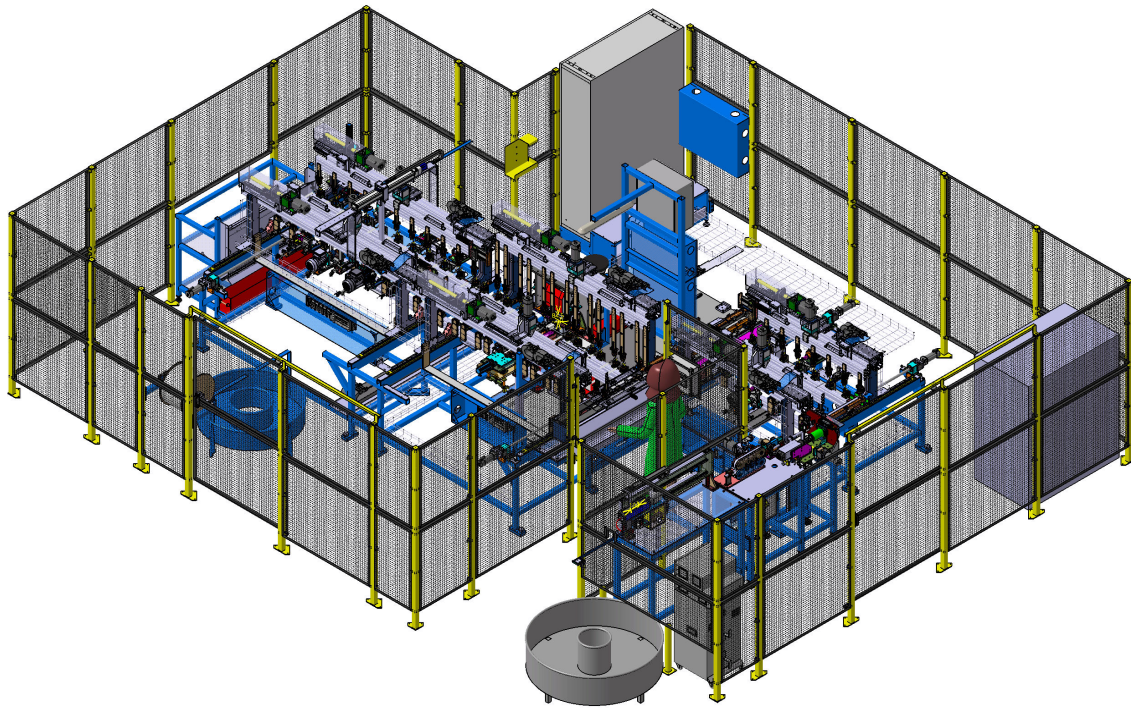
## 2.2. Process and Components

Figure 1 presents the constitution a typical control cable and respective components: 1- first injection terminal (Zamak), 2-inner tube, 3-spiral, 4-outer coating, 5-star tube, 6-identification tag, 7-spiral terminal, 8-s injection terminal (Zamak), and 9-metal cable. The fabrication process begins by cutting and coating the metal cable that serves as force transmitting element of the control cable (9 in Figure 1). Following, one metal cable end is stripped of the coating, prepared, and the first Zamak injection takes place. Next, the cable with one injected terminal and assembled with the inner coating is inserted into the fabricated spiral, i.e., with coating, star tube, rubber or grommet, and spiral terminal. This work specifically addresses the stage of injecting the spiral terminal over the outer coating involving the spiral, task executed by an automated assembly line. This line performs most of the steps associated with assembling various cables of different lengths and complexities. Once the cables leave this line, they are transferred to another assembly line where the assembled metal cable (with inner coating and injected with the first Zamak terminal), is injected at the opposite cable end with the second Zamak terminal, which blocks the cable inside the spiral and finalizes the cable fabrication process.



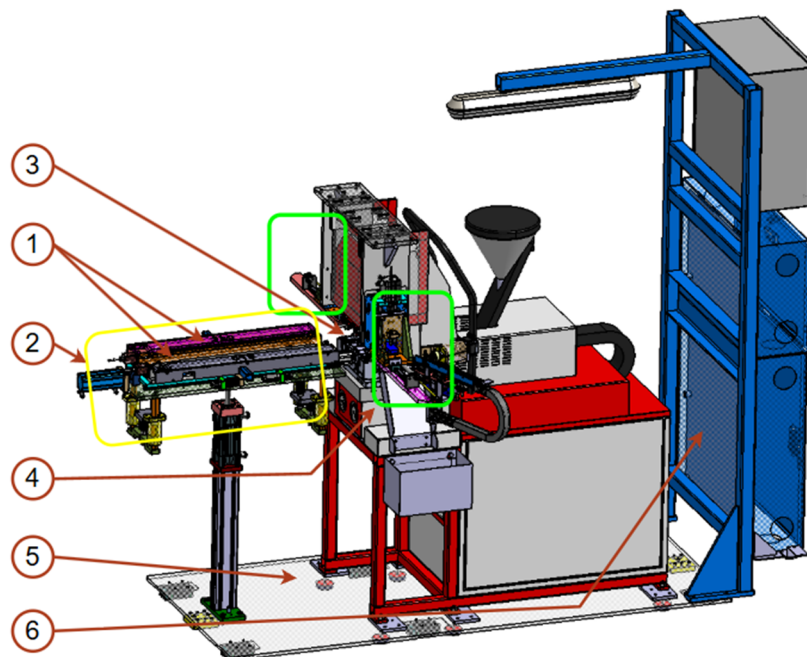
**Figure 1.** Control cable and its components.

The spiral preparation process is now detailed, and the assembly line in which is made is shown in Figure 2. This process begins at the pre-injection station. The unwinding of the first coil feeds the spiral, which is covered by the outer coating. In this first zone, the spiral's length is measured, cut, and transferred to the deburring and grinding station. At this station, the burrs on the inner edge of the spiral and the outer edge of the coating are removed. After this step, the spiral is transported to the diameter control and air blowing subset, where the outer diameter is measured, and the interior is cleaned with an air blow. Finally, the operator inserts the star tube and/or grommet onto the outer coating.



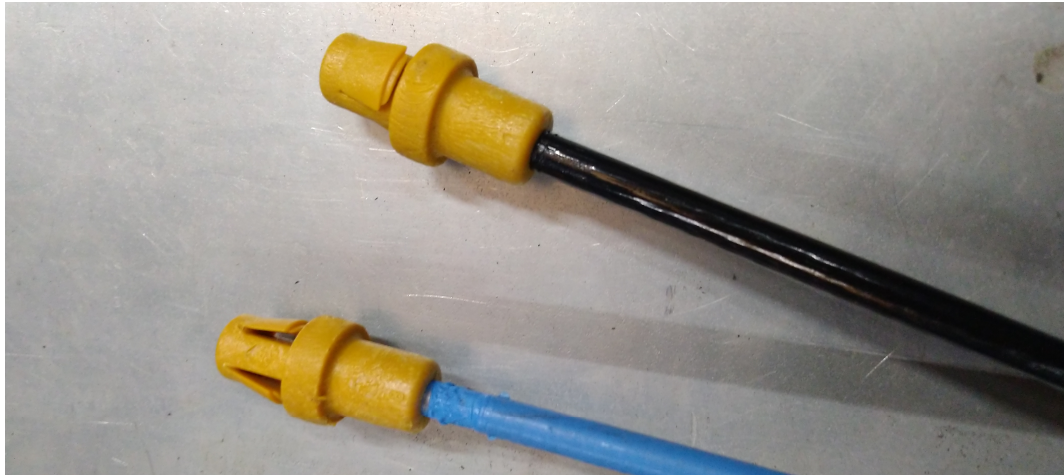
**Figure 2.** Assembly line for control cable fabrication.

The spiral then moves to the over-injection station, represented in Figure 3, being transported by the handling system to the spiral terminal, whose function is to inject the two spiral terminals onto the outer coating. Once this task is completed, the handling system sequentially transports the spiral subset through several steps at the remaining subsets: spiral terminal drilling, spiral cleaning, inner tube assembly, inner tube adjustment, flaring, calibration, cap detection, lubrication, and output. As the spiral subset moves from the pre-injection to the over-injection station, the jig (1), which has the capacity of holding two spiral subsets, and the supporting platform (2) movement, provide the spiral the required transportation to the injection area of the station (3). The spiral subsets' correct positioning is assured by two mould guides (4). The base (5) includes all process components, including the main structure (6) that holds the control panel of the injection machine and various pneumatic and electrical connections.



**Figure 3.** Spiral terminal over-injection subset.

The machine injects spiral terminals made of polyoxymethylene (POM), a thermoplastic with a melting point of 165 °C. To achieve this purpose, it uses a progressive heating system to melt the POM, supplied in the form of granules, until it reaches the injection chamber. Here, a piston compresses the POM through the injection nozzle, which is heated by electrical resistances to prevent the POM from cooling and solidifying prematurely during injection. The result of this operation is the spiral terminal over moulded onto the outer coating, as shown in Figure 4.

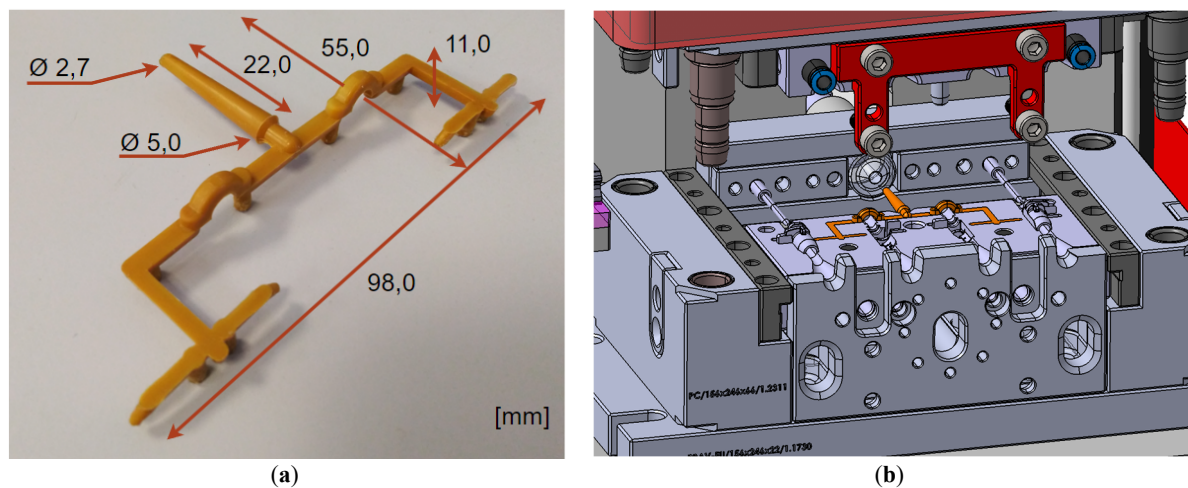


**Figure 4.** Spiral terminal over moulded onto two different spiral subsets.

### 2.3. Problem Description

The over-injection of the spiral terminal onto the outer coating was originally implemented using hot-runner injection mould technology. In this configuration, the injection nozzle establishes direct contact with the mould cavity, allowing the molten polymer to be delivered without the formation of intermediate flow channels. As a result, the injected material solidifies exclusively within the cavity of the component, eliminating the generation of auxiliary material such as runners or gates. Once the moulding cycle is completed and the part has cooled, the terminal can be released directly, as no separation from a feeding system is required. From a production standpoint, this solution minimizes material waste and simplifies post-processing operations. Despite these advantages, the use of hot-runner moulds introduces technical and economic challenges. Owing to the relatively long injection nozzle required to reach the cavity, additional external heating is necessary to maintain the polymer in a molten state along the entire flow path. This requirement is particularly critical at the nozzle tip, where heat losses can lead to premature solidification, flow instability, or injection defects. Furthermore, hot-runner systems involve more complex thermal management, higher manufacturing precision, and specialized components, which translate into increased acquisition and maintenance costs. These factors can become limiting in applications where cost efficiency and operational simplicity are prioritized.

In response to these constraints, subsequent modifications to the injection process led to the adoption of cold-runner injection moulds for the spiral terminal. In this alternative configuration, the injection nozzle is significantly shorter and does not require continuous thermal regulation along an extended flow path, thereby reducing or even eliminating the need for external heating elements. This simplification contributes to lower tooling costs, reduced energy consumption, and easier maintenance. However, the cold-runner approach inherently requires a dedicated feeding system to distribute the molten polymer from the nozzle to the mould cavities. As the material in these runners cools and solidifies during each injection cycle, a gate is inevitably formed and remains attached to the mould after part ejection, which introduces new challenges related to material handling and process continuity. The issue identified in the control cable assembly process results from this design change in the spiral terminal injection stage and the introduction of a gate with a mass of 24.60 g (Figure 5a) in the lower injection mould (Figure 5b). Contrary to the initial design intent, this gate is formed due to the cooling and solidification of the POM in the feeding system of the moulds. Thus, it is necessary to design an automated system to remove the plastic gate from the injection area. After each injection, the injection machine becomes inoperative, causing the entire assembly line to halt until the gate is removed.



**Figure 5.** (a) POM gate resulting from the injection process in the injection machine (b) lower injection mould with gate.

#### 2.4. Objectives, Requirements, and Limitations

The main objective of this work involves the design of an automated system, which should be coupled to the injection moulding machine, which can remove the POM gate generated at the lower half of the mould after each POM spiral terminal injection cycle. The proposed transportation solution must not obstruct the injection area and must adapt to the available space to avoid modifications to the existing machine and equipment. The company typically uses alternate current (AC) electric motors in applications requiring high precision. These motors are characterized by high rotational speeds, ranging from 750 to 3000 rpm, which are often excessive for their intended applications. To address this limitation, the company employs gearboxes to reduce rotational speeds. However, this approach has drawbacks, including increased space requirements, complexity, and cost. As a result, the company plans to implement stepper motors, which use direct current (DC), offer high precision, are easy to install, cost-effective, and operate at lower rotational speeds, eliminating the need for gearboxes. Therefore, a critical requirement for this project is the use of stepper motors to transport and remove the gate from the injection area (horizontal movement of the system). In addition to the primary functional objectives, several technical and operational requirements were defined to guide the development of the automated gate transport system, as follows:

- From an economic perspective, the solution was required to achieve a favourable balance between performance and cost, ensuring that the overall investment remained as low as possible while fully satisfying the functional demands of the application;
- Given the inherent variability associated with injection moulding operations, the system was also required to incorporate adjustment capabilities that allow fine correction of the gate gripping and fixation position. This adjustability is essential to accommodate small deviations in gate geometry or positioning, thus ensuring reliable operation over extended production periods without the need for frequent recalibration or manual intervention;
- Ease of assembly and maintenance was identified as another key requirement, to assure minimal downtime and rapid servicing. The system architecture should be conceived to allow straightforward disassembly, component replacement, and access to critical elements, using standardized parts wherever possible to simplify logistics and reduce maintenance complexity;
- To enhance durability and operational reliability, the design sought to eliminate direct contact between components experiencing relative motion. By avoiding sliding interfaces and favouring guided or rolling mechanisms, the system should minimize friction-induced wear, reduce noise generation, and lower long-term maintenance requirements;
- The physical space available to install the automated transport system was strictly defined by the company and imposed as a non-negotiable constraint throughout the design process. All mechanical arrangements and movements were therefore developed to operate entirely within the allocated space, aiming to ensure integration with the existing injection moulding machine without structural modifications.

### 3. Results

#### 3.1. Preliminary Design

The designed system presents a solution that involves displacement between two points and a fixation mechanism. The latter will be used to fix and release the gate during the process, to allow for its transport. Movements are required to remove the injection assembly from the lower mould through an upward movement, and to extract the injection assembly from the injection area horizontally.

##### 3.1.1. Concept Generation and Alternatives

To ensure a comprehensive exploration of possible solutions, the conceptual design phase considered multiple actuation and transport principles capable of fulfilling the required gate extraction and displacement functions. The functional requirements identified in Section 2.4 were decomposed into two main actions: (i) gate gripping and vertical extraction; and (ii) horizontal transport from the injection zone to the collection area. Based on this decomposition, four alternative concepts were generated:

- Concept A—Pneumatic linear transport: Horizontal displacement performed by a pneumatic cylinder, combined with a pneumatic gripper for fixation and a second actuator for vertical motion;
- Concept B—Electric linear actuator: Use of an electric linear actuator (lead screw type) integrating motor and transmission in a single unit;
- Concept C—Spindle drive system: Rotation-to-translation conversion using a motor-driven lead screw and guided carriage (as illustrated in Figure 6);
- Concept D—Rack and pinion system (selected solution): Conversion of rotational motion into linear displacement through a pinion–rack mechanism driven by a stepper motor (Figure 7).

##### 3.1.2. Concept Evaluation and Selection

To ensure an objective selection of the most suitable solution, a qualitative decision matrix was established based on the main design requirements defined in Section 2.4. The evaluation criteria included:

- Integration within the available space;
- Interference with the injection zone;
- Positioning precision and repeatability;
- Ease of integration with existing systems;
- Cost and implementation complexity;
- Maintenance requirements.

Each concept was qualitatively assessed using a three-level scale (Low, Medium, High). The results are summarized in Table 1.

**Table 1.** Concept evaluation matrix [25–27].

Criterion	Pneumatic Cylinder	Electric Linear Actuator	Spindle Drive	Rack & Pinion
Space adaptability	Medium	Low	Low	High
Interference with injection zone	High	Medium	High	Low
Precision and repeatability	Low	High	High	Medium-High
Integration complexity	Low	Medium	Medium	Medium
Cost	Low	High	Medium	Medium
Maintenance	Low	Medium	Medium	Low

The final system architecture results from the independent evaluation of the two main functional requirements: (i) gate gripping and vertical extraction; and (ii) horizontal transport between the injection and collection zones. The selection of the actuation principles for each function was guided by the criteria presented in Table 1, with particular emphasis on spatial integration, interference with the injection area, and implementation constraints defined by the industrial environment.

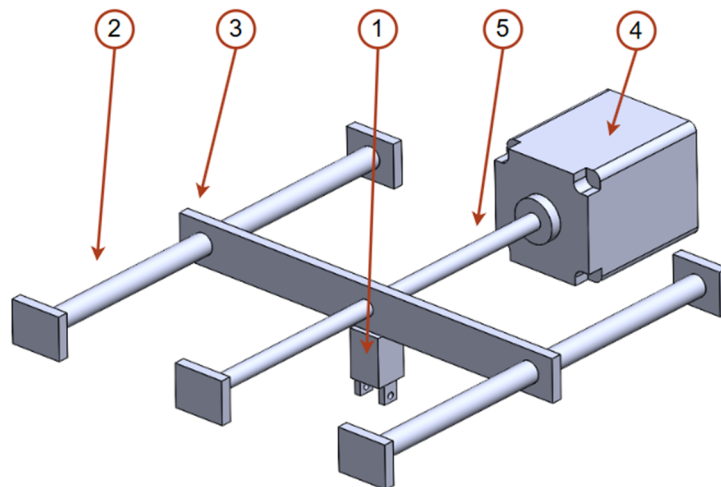
For the vertical extraction and gripping function, pneumatic actuation was selected as the most suitable solution when compared to electric alternatives. This decision is supported by several factors:

- Pneumatic actuators present a high force-to-size ratio, which is particularly advantageous given the restricted installation space available near the injection mould. The selected actuator can deliver the required extraction force with a compact footprint, thus respecting the spatial constraints identified in Section 2.4;

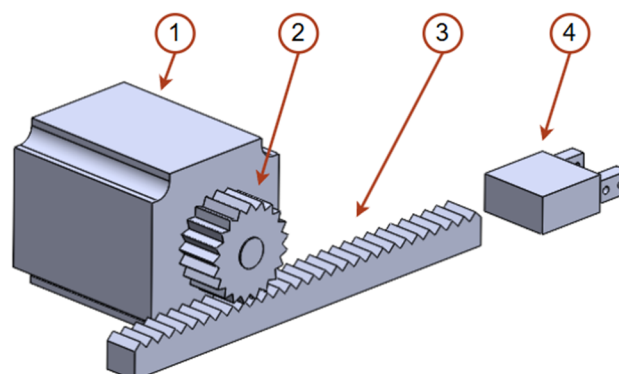
- The desired function does not impose major requirements in terms of positioning accuracy or trajectory control. The movement is limited to a short stroke, with fixed end positions corresponding to the gate engagement and extraction points. Under these conditions, the binary operation (extend/retract) of pneumatic cylinders assure the required system performance;
- Pneumatics is further justified by the existing compressed air infrastructure of the assembly line, which allows immediate implementation without the need for additional power electronics or control systems. This feature contributes to reduced cost and system complexity, as reflected in the evaluation matrix;
- Electric actuators, although with higher precision and controllability, were considered unnecessary for this specific function. Their higher cost, increased integration complexity, and larger installation requirements do not provide a benefit in performance for a simple vertical displacement task;
- Pneumatic grippers are widely used in industrial handling applications due to their robustness, fast response, and reliability, which makes them well-suited for repetitive operations such as gate fixation and release.

The selection of the horizontal transport mechanism was subject to an additional constraint imposed by the company, namely the requirement to use an electric motor-based solution. As a result, the conceptual evaluation focused on two main alternatives: rack and pinion mechanisms, and spindle drive systems:

- In the first option, presented in Figure 6, the system's movement is initiated through the rotation of the motor (1) and, consequently, the pinion (2). The teeth of the pinion, engaged with the teeth of the rack (3), act as a gear, since the rack can move freely along its length. Due to the geometry of these components, the rotation movement is converted into linear movement. At the end of the rack is the gate fixing device (4), which accompanies the forward and backward movement of the rack;
- In the second option, shown in Figure 7, the movement of the fixing device (1) is guided by two shafts (2), which in turn support a moving component (3). Its displacement is due to the rotation of the electric motor (4) associated with a spindle drive shaft system (5). The fixing device will be attached to the moving component, thus allowing the gate to be transported as the motor rotates and its movement is transformed into linear movement.



**Figure 6.** Initial sketch of the application of spindle drive shaft.



**Figure 7.** Initial sketch of the application of rack and pinion.

Although both solutions can convert rotational motion into linear displacement with adequate precision, their suitability differs significantly when evaluated against the integration and spatial criteria. Ultimately, the rack and pinion mechanism was selected as the most appropriate solution for horizontal transport, substantiated as follows:

- The spindle drive system offers high positioning accuracy and smooth motion, as reflected in the evaluation matrix. However, its implementation requires a fixed guiding structure and a lead screw aligned with the full stroke length, which must remain permanently installed within or adjacent to the injection area. Given the limited space and the need to preserve access to the mould for operation and maintenance, this configuration was considered highly intrusive. Additionally, the presence of continuous mechanical elements within the working zone increases the risk of interference with other machine components and complicates system integration;
- The rack and pinion solution provides a more flexible configuration in terms of spatial integration. The main advantage of this mechanism lies in its ability to allow the active transport elements to enter and exit the injection zone dynamically, rather than occupying it permanently. This characteristic significantly reduces interference with the injection process and aligns with the requirement of non-intrusive integration without structural modification of the existing equipment.
- In terms of performance, the rack and pinion system provides sufficient positioning accuracy and repeatability for the application, particularly when combined with stepper motor control and position sensors. Although slightly less precise than a spindle system in absolute terms, this difference is not critical for the transport of the gate, which does not require micrometric positioning;
- The rack and pinion mechanism offers advantages in terms of mechanical simplicity, robustness, and ease of maintenance, due to the absence of long slender rotating elements such as lead screws. Its modular nature also facilitates adjustment and alignment during installation.

### 3.2. Design

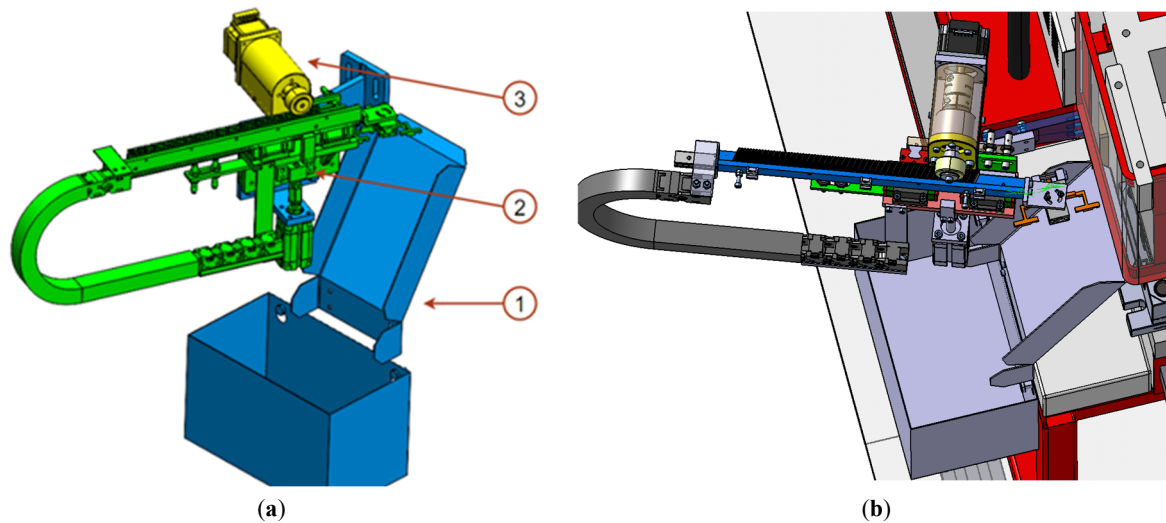
#### 3.2.1. Final equipment

The development of the system began by defining the required movements and actions, and their decomposition into movements that can be performed by actuators, namely linear trajectories obtained by the advance or retreat of the moving component, rotation provided by rotary actuators, or fixation achieved by clamps. Thus, the operation of the system was designed using three distinct movements so that the automated system can remove the POM gate from the injection machine. Two pneumatic actuators are also used in this system, as well as standardised elements such as screws, air tubes, and position sensors, and components designed specifically for this project, such as bases, clamps, mounts, among others.

The final system, shown in Figure 8a, weighs approximately 11 kg and is composed by three sub-assemblies, each of them responsible for a distinct action. The base sub-assembly (1) has no moving parts and its main functions are to support the other two subassemblies, secure the pneumatic actuator that performs the vertical movement, and collect the gates. It also performs actions such as establishing the slope of the rack's direction of movement relative to the injection zone and guiding the vertical movement through guide rails and skids. The mobile sub-assembly (2) is responsible for three actions. First, vertical movement is accomplished through a DNA-25-30-A-P-A pneumatic actuator, which allows the pneumatic gripper to advance over the gate, as well as its extraction from the injection zone. The use of a ball joint at the end of the rod and skids, which slide on the guides in the base subassembly, ensure the movement of the subassembly with high precision, repeatability, low friction, and durability. Second, horizontal movement that enables the transport of the gate between the injection zone and the collection zone, is carried out, as previously mentioned, by the electric stepper motor associated with a rack and pinion. Similarly to the previous movement, the rack moves on skids over a rail, and the initial and final positions are detected by M8 inductive sensors. Third, fixing of the gate in an MHZL2-20D pneumatic gripper is done by means of two clamps, fixed to the teeth of the pneumatic gripper. Several components and details were designed to allow the adjustment of the position of the fixing clamps in the three directions of movement, as well as the rotation of the gripper in relation to the axial direction of the spindle. The motor sub-assembly (3) supports and incorporates the electric motor into this specific application, which involves the use of an elastic coupling to connect the electric motor to the shaft. In turn, the shaft is supported by ball bearings. In addition to supporting the shaft and allowing it to rotate, these bearings also absorb axial loads resulting from the helical teeth, which are thus not transmitted to the electric motor shaft. The shaft is also responsible for securing the gear wheel. The subassembly has other components such as the fixing flange, the motor base, and the motor mount, which allow the vertical position of the subassembly to be adjusted and thus regulate the contact between the rack and pinion teeth.

Once implemented in the injection machine, as shown in Figure 8b, the simultaneous use of all these components allows the designed system to: remove the gate from the lower injection die and, consequently,

continue the operation of the injection moulding machine, as well as the respective assembly line; provide a transport solution that allows components of the automated system to enter and exit the injection zone to remove the gate, without any alteration to the existing process and components; and collect the gates in a deposit.



**Figure 8.** (a) system sub-assemblies: (1) base, (2) mobile sub-assembly, and (3) motor sub-assembly, and (b) system mounted on the injection moulding machine.

### 3.2.2. Design Elements

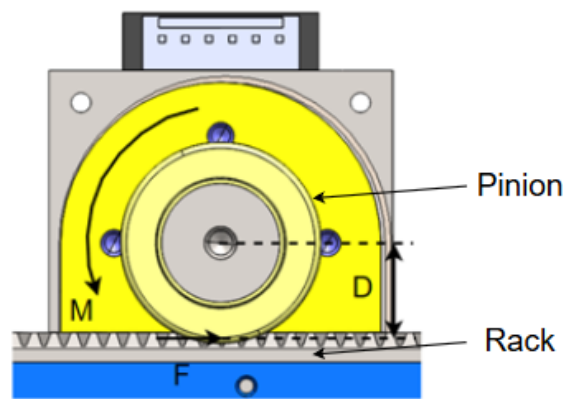
Since none of the designed parts are subjected to considerable stress, no Finite Element Method analysis was required for their design. Therefore, the design focused mainly on the actuators and electric motor. Regarding the pneumatic gripper, one of the main problems was the limited space available. Thus, the model MHZL2-10D from SMC Corporation was selected. Its small size, specifically  $57 \times 35 \times 16 \text{ mm}^3$ , combined with a gripping force of 17 N, when operating with a pressure of 6 bar, enables it to be used without interfering with the existing components, and ensures that the gate is clamped and that the pincers are transported at its ends. This model also presents a long opening range, namely 8 mm, which makes it possible for the grippers to advance over the gate without interference, and the ability to perform 120 cycles per minute, which corresponds to an opening and closing cycle of the pneumatic gripper in 0.50 s, considered sufficient for the application.

After analysing the three-dimensional (3D) model of the system, it was determined that a 30 mm stroke was necessary for the vertical movement cylinder. The advance force was established using the 3D model to certain the mass ( $m$ ) of the components that the actuator transports. These components include the electric motor sub-assembly and the mobile sub-assembly, in a total of 5.79 kg. The next step is calculating the advance force ( $F_a$ ), including the gravitational acceleration ( $g$ ), a factor of safety ( $fs$ ) defined by the company, and the load factor ( $\eta$ ) of the respective actuator application, which corresponds to the case with the load applied throughout the entire action of the actuator [26]:

$$F_a = (m \times g \times fs) / \eta = (5.79 \times 9.81 \times 1.50) / 0.5 = 170.23 \text{ N}$$

After checking several available actuators, the pneumatic actuator, from Festo, ADN-25-30-A-P-A, was selected. It has  $F_a = 295 \text{ N}$  when operating at 6 bar of air pressure, making it sufficient for this application.

The use of an electric stepper motor is a requirement of the project. This type of motor stands out for its use of DC, high precision due to the rotation of the motor shaft in constant steps, low cost, and suitability for undemanding applications, as it is the type of electric motor with the lowest power-to-weight ratio [28]. Thus, the operating characteristics of these motors are ideal for the application in this project, which requires precise control of the start and end positions of the pneumatic gripper, and a more efficient solution with a lower initial investment than AC motors. Motor dimensioning begins by determining the effective torque ( $B_e$ ) that the motor needs to produce. This torque corresponds to the moment required for the pinion to cause the rack to move, which is determined by considering the tangential force ( $F_t$ ) acting between the pinion and the rack, and the distance between the axis of rotation of the motor shaft and the point of contact between the pinion and the rack ( $D$  in Figure 9).



**Figure 9.** Diagram showing the moment generated by the rack's translation.

$F_t$  is the force applied by the pinion to the rack to produce the horizontal movement of the components associated with this operation, and is determined by the weight of these components, which is obtained by the product between  $g$  ( $9.81 \text{ m/s}^2$ ) and the components' weight, a value obtained by assigning the materials to the components and using the CATIA V5 tools to determine their mass (1.79 kg), resulting in a force of 17.54 N. The  $D$  variable corresponds to half the working diameter of the pinion, namely 15.92 mm. Once these values have been determined,  $B_e$  is calculated, a value that is affected by  $f_s = 2$  indicated by the process engineering department for this application:

$$B_e = M \times f_s = F_t \times D \times f_s = 17.54 \times (15.92 \times 10^{-3}) \times f_s = 0.279 \times 2 = 0.56 \text{ Nm}$$

After consulting several suppliers, a motor with a maximum torque of 0.72 Nm and 0.60 Nm of holding torque was selected, which is sufficient for this application, and a resolution of  $1.8^\circ/\text{step}$ , i.e., the rotation of the motor shaft is carried out at intervals of  $1.8^\circ$ . The SCA5618X2804-A NEMA 23 from Nanotec is a compact electric motor that only occupies a volume of  $56 \times 67 \times 65 \text{ mm}^3$  and has a low mass (0.45 kg), thus making it suitable for insertion into the electric motor sub-assembly. The electric motor operates with a current of 2.8 A and 12 V, which can be supplied by the assembly line power supply.

The rack and pinion are mechanical components that fall into the category of gears, i.e., a pair of toothed wheels [29], and were selected because they allow the rotational movement generated by the electric motor to be converted into translational movement. A helical gear was also selected for these components. As a result, contact between the pinion and the rack is initiated at a point that extends along the line of contact between the teeth of these components, resulting in gradual meshing of the teeth and, thus, smoother movement and quieter operation when compared to straight teeth. It is also worth noting the higher strength of helical teeth, and consequently greater load capacity, when compared to straight teeth, since the contact profile between the teeth is wider. However, the dimensions of these components must be minimised to reduce their mass, and consequently the force required by the electric motor. After consulting several catalogues, the F01L30A13 pinion and 016MR050C10 rack from Apex Dynamics Inc. (Taichung City, Taiwan) were selected. These components have helical teeth and are relatively small in size, which matches their application in the project. The main characteristics of the rack are its width of 15 mm and length of 275 mm, corresponding to a mass of 0.437 kg, while the mass of the pinion is 0.103 kg.

### 3.2.3. Materials and Processes

Originally, machining was chosen as the basic manufacturing process for the components of the developed system, as it stands out for its high precision and ability to produce the desired components, even if they have complex geometries, in a relatively short time and at an acceptable price. Other components, such as those manufactured from sheet metal, involve manufacturing processes such as laser cutting, bending, and welding. The materials selected for the different components of the automation system mainly considered the operating environment and the functionality of the respective component. About the working environment, conditions are relatively normal, with most components only exposed to atmospheric air, meaning that the only problem will be metal oxidation. Galvanisation was therefore selected as the protection method. This process coats metal components with a thin layer of zinc, which acts as a sacrificial metal, subject to oxidation, while the base metal is preserved [30]. For sheet metal components, stainless steel was chosen as a method of protection against corrosion, since it is a material already widely used for these components. There is no economic advantage in using untreated sheets to treat them after manufacturing the desired components (an action that would also increase delivery times).

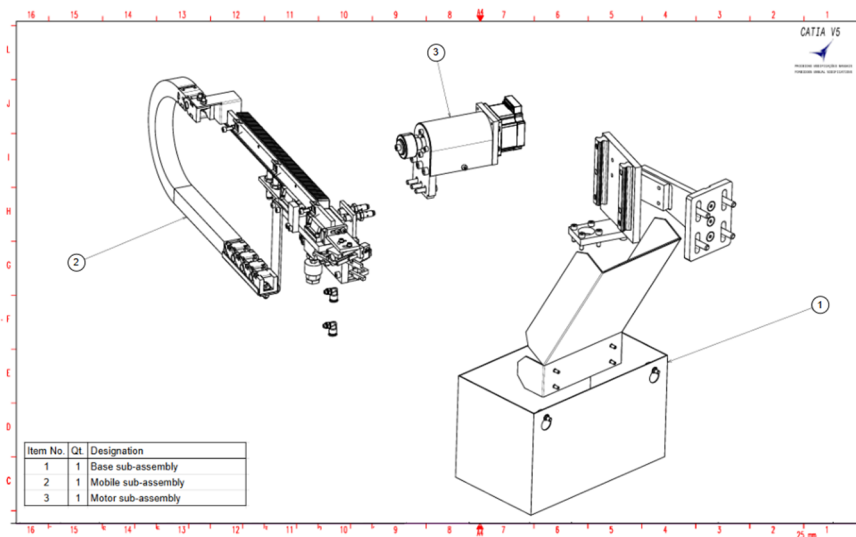
Regarding the functionality of the respective component, this characteristic relates the loads and stresses to which it is subjected, with the performance of the component within the system and the wear it will endure. The main components to consider are machined parts, since the other components, such as sheets, are not subjected to significant stresses. Thus, with regard to machined parts, there are two main possibilities:

- **Long-lasting component:** It is usually stationary and mostly exposed to forces such as bending and torsion, and it is used in applications such as supports, bases, plates, and brackets. High material stiffness and mechanical strength to the stresses to which these parts are subjected are required to prevent misalignment of the components they support, which causes greater wear and possible collisions. DIN Ck45 (ISO C45E) steel was selected. This is a carbon structural steel, a material frequently used in the general mechanical construction industry due to the good relationship between its mechanical properties and its low cost. This steel has other characteristics that favour its selection, such as good machinability and the possibility of applying various treatments, such as galvanisation, tempering, and nitriding [31]. Components manufactured from this material are subsequently galvanised to increase their corrosion resistance;
- **Wear component:** involves wear caused by friction resulting from contact and relative movement between two or more components. The service life of these components must be maximised to avoid replacement, so a relatively high surface hardness is required, but also good toughness for improved response to impacts. This possibility includes components such as clamps and the shaft associated with the electric motor. The clamps are wear components whose operation involves contact with polymeric material at relatively high temperatures, namely the POM gate a few seconds after being injected. Therefore, C265 (ISO X153CrMoV12) was selected, a tool steel with good nitriding treatment capacity and very good wear resistance [32]. PM300 (ISO 40CrMnNiMo8-6-4) nitrided, an alloy structural steel suitable for machine parts, was selected for the shaft. The nitriding treatment not only gives the shaft greater surface hardness and consequently greater wear resistance, but also provides higher fatigue resistance, which maximises the component's service life [33].

The sheet metal parts will be manufactured in AISI 304 stainless steel (ISO X 5 CrNiMo 18 10). The use of steel sheet gives these components the necessary stiffness, as well as the possibility of bending and welding to achieve the required geometry. As it is stainless, high corrosion resistance is guaranteed [34]. This material is applied to components such as the electric motor protection sheet, the gates collection box, and the articulated rail supports.

### 3.2.4. Physical Construction

The assembly was initiated once all the ordered components had been gathered, namely the mechanical parts, standard components such as the electric motor and bearings, as well as the pneumatic actuators and respective accessories. Initially, the three subassemblies were assembled individually, using the respective assembly drawings to guide the process. These provide all the necessary information for correct assembly, as shown in Figure 10a, such as the position of the parts, their fixation, and the standardised components to be used in the respective application. The exploded view of Figure 10b allows for a better visualisation of the individual components that make up the subassembly, which would not be possible otherwise, thus leading to a better understanding of the subassembly and easier assembly.



(a)

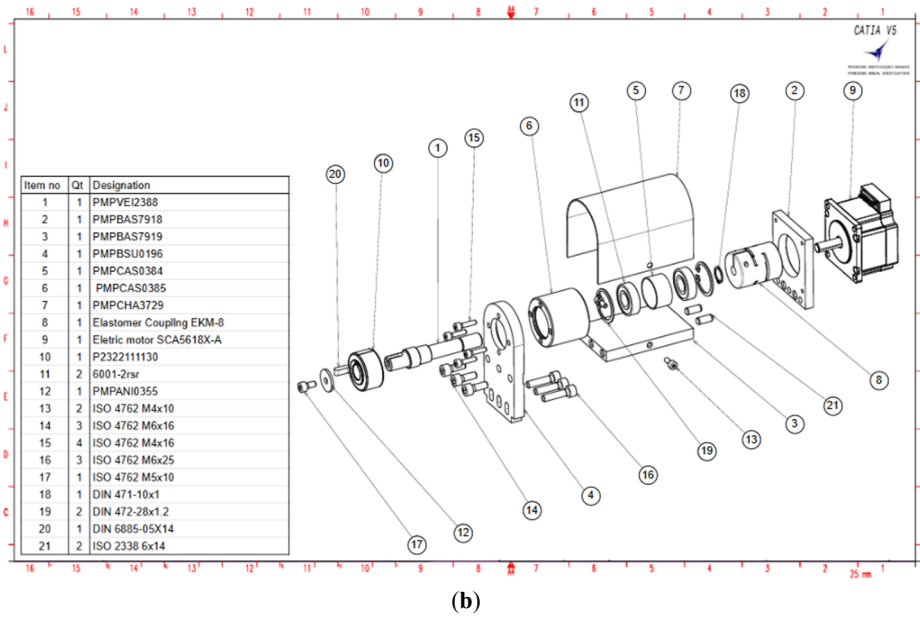


Figure 10. (a) assembly drawing (b) subassembly motor drawing.

Assembling these subassemblies in the workshop enabled checking several aspects before proceeding with installation on the assembly line, such as adjusting the position of the pneumatic grip on its support, the alignment between the sensor supports and the elements they will detect, the position of the shaft relative to the rack, and its rotation on the ball bearings, amongst others. Once on the assembly line, the appropriate holes were drilled in the side plate of the injection moulding machine to secure the assembly. This process was followed by the establishment of the respective pneumatic and electrical connections to the assembly line’s panel and air line. After changing the assembly line’s operating program and making minor adjustments to the clamp position and motor rotation speed, it was possible to check that the automated system was working correctly. The final assembly is shown in Figure 11.

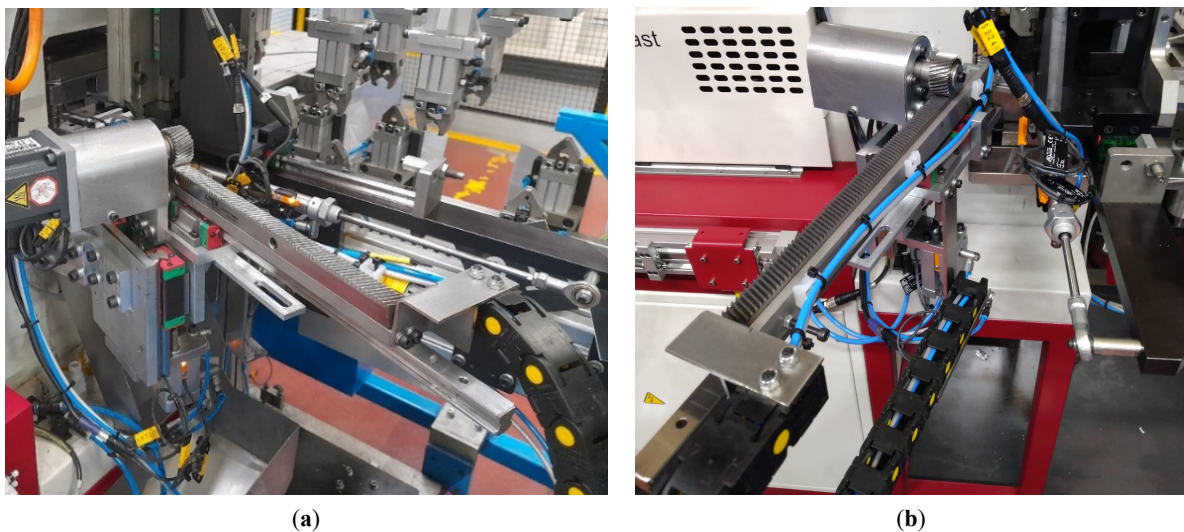


Figure 11. Assembly mounted on the injection moulding machine: view 1 (a) and view 2 (b).

### 3.2.5. Performance Evaluation

After the functionality assessment of the automated gate removal system, a quantitative evaluation of its operational performance was carried out to assess reliability, robustness, and suitability for continuous operation in a production line. This evaluation focuses on indicators such as failure modes, occurrence rates, and system endurance in terms of operating cycles. The equipment performance was assessed through extended operation under representative production conditions. Since continuous long-term measurements were not available at the time of writing, a structured evaluation was defined based on (1) observation of system behaviour during pilot operation; (2) identification of critical failure modes; (3) estimation of occurrence probabilities based on actuator

specifications, cycle time, and mechanical constraints; and (4) extrapolation of performance over extended cycles using conservative assumptions.

A total equivalent of 120 operating hours was considered, corresponding to approximately 86,400 cycles, assuming an average cycle time of 5.0 s per injection/removal sequence, as field measurements indicate. The main identified failure modes considered in the evaluation are as follows:

- Non-grabbed gate: failure of the pneumatic gripper to correctly clamp the gate;
- Misrelease: release of the gate outside the intended collection area;
- Transport failure: incomplete or interrupted horizontal displacement;
- Jamming event: mechanical obstruction during movement (rack, guides, or vertical actuator);
- Sensor-related fault: incorrect position detection affecting sequence execution.

Table 2 summarizes the estimated occurrence of each failure mode during the evaluated operating period. From these values, the global failure rate is estimated at 0.040% per cycle, corresponding to approximately 40 failures per 100,000 cycles. This results in an operational success rate of 99.96%, which is considered acceptable for this type of auxiliary automation system, especially given the absence of active feedback control or vision-based correction.

**Table 2.** Estimated failure rates and occurrence during operation.

Failure Mode	Estimated Probability per Cycle (%)	Occurrences (per 100,000 Cycles)	Observed/Estimated Causes
Non-grabbed gate	0.020	20	Misalignment, variability in gate geometry
Misrelease	0.010	10	Timing mismatch, gripper release position
Transport failure	0.005	5	Stepper motor positioning or rack engagement
Jamming event	0.003	3	Debris accumulation or mechanical interference
Sensor-related fault	0.002	2	Signal noise or misalignment of inductive sensors

The evaluated operational period of 86,400 cycles provides an initial indication of system durability. Based on component specifications:

- The gripper is rated for >10 million cycles, indicating negligible wear within the evaluated period;
- The stepper motor operates well below its torque capacity, reducing thermal and mechanical stress;
- The rack and pinion system, combined with guided motion and low friction interfaces, minimizes wear.

Since no critical degradation mechanisms were identified within the evaluated cycle range, preventive maintenance actions are limited to periodic cleaning of guides and rack (recommended every 100,000 cycles), inspection of gripper alignment and fastening elements, and verification of sensor positioning. Overall, the system demonstrates robust performance that is compatible with continuous industrial operation, thus supporting the feasibility of its implementation beyond economic considerations.

### 3.2.6. Economical Study

The main objective of the economic study carried out is to determine the time it takes for the implemented system to generate profit, i.e., the ROI. In this situation, the ROI can be calculated by the ratio between the profit generated by the implementation of the system and the respective cost. To this end, it is first necessary to determine the total cost of the operation, which consists of three main parts, namely the manufacture of the designed parts that make up the subassemblies, the purchase of standardised components, such as the ball bearing, pneumatic actuators, bolts, and washers, and the work performed by the process engineering department team. These values are shown in Table 3. Since the operating cost, which includes the compressed air used by the pneumatic actuators and the electricity used by the sensors and electric motor, is a very small part of the operating cost of the assembly line, this figure has been omitted. As regards the project team, it consisted mainly of two mechanics, a programmer and a mechanical engineer (the supervising mechanical engineer was not included in the costs, given the relatively low number of hours spent on the project, nor were the other team members, as their work was of an auxiliary nature and was not remunerated by the company). The initial phase of the project, carried out by the mechanical engineer, lasted approximately one month and included tasks such as the design of 3D components and assemblies, integration of the 3D model into the assembly line, 2D drawings, dimensioning, and costing. The programmer was responsible for creating a new work cycle for this new system and implementing it on the line, a task completed in two days. After all components had been delivered, which took around a month, the assembly of the sub-assemblies in the workshop was carried out in two days by a mechanic. Afterwards, the system was implemented on the assembly line by two mechanics, the programmer and the mechanical engineer, and this phase included

tasks such as assembly, pneumatic and electrical connections, connection to the programmable logic controller (PLC), fine-tuning and initial testing, which lasted approximately one week.

**Table 3.** Acquisition costs of the automated system.

Item	Cost (€)
Base sub-assembly	687.40
Mobile sub-assembly	1018.50
Motor sub-assembly	401.25
Standardised components	699.42
Process engineering team	5200.00
Total	8006.57

With regard to the profit generated by the implementation of the system, the profit generated by the automatic assembly line is considered in relation to the jobs that are being used while it is not operational. Thus, the company stated that it is incurring an operating cost of approximately €4000 per month, mainly in labour, to produce the cables on manual lines that could be manufactured on the automatic line if it were already operational. Based on the cost of €8006.57 to implement the automated transport system and the savings generated of €4000 per month, the ROI estimation is 2.0 months. Therefore, it is concluded that the ROI will be achieved within two months, a very positive figure for the company, given that it is less than the time taken to complete the project, namely 2 months and 3 weeks, approximately.

#### 4. Conclusions

This work addressed a practical and economically relevant limitation in an automotive control cable production line, namely the interruption of the over-injection process caused by the formation of a polymeric gate when adopting a cold-runner mould configuration. By following a structured methodology (i.e., DSR), a compact and automated transport system was conceived, designed, manufactured, and validated under real industrial conditions. The developed solution successfully removes the POM gate from the lower mould after each injection cycle without interfering with the injection area or requiring structural modifications to the existing equipment. The solution combined a rack-and-pinion mechanism driven by a stepper motor for horizontal displacement with pneumatic actuation for vertical motion and gripping, and proved to be technically adequate by ensuring reliable operation, with an operational success rate of 99.96%. The modular architecture and integrated adjustment features allow fine positional tuning, accommodating process variability and facilitating maintenance and future adaptations. The system assured continuous operation of the automatic assembly line by eliminating manual intervention in gate removal, thus reducing operator exposure to repetitive and potentially harmful tasks. The mechanical design ensured low friction, reduced wear, and appropriate load capacity. Proper material selection and surface treatments enhanced durability and corrosion resistance in the industrial environment. The economic evaluation demonstrated strong financial viability, with a ROI of approximately two months, a very positive figure, since it is faster than the time invested to complete the project. This short payback period highlights the effectiveness of targeted automation solutions when aligned with clearly defined operational bottlenecks. The conceptual principles and mechanical architecture presented in this study can be adapted to other polymer processing environments where gate or runner removal compromises productivity. Having monitored the system's operation, assessed its operational effectiveness and identified the causes of the existing failures, however rare they may be, it is important to note that the system could be improved in further work. To this end, one possible solution would be to implement systems capable of identifying if the gate has been correctly removed from the injection mould, if it has not fallen out during transport, and if it has been correctly deposited in the scrap container. This stage could be based on the methodology adopted in Ribeiro et al. [20] which, as previously mentioned in Section 1, led to the implementation of a fault detection system in the respective process.

#### Author Contributions

J.P.M.P.: conceptualization, investigation, data curation, visualization, writing original draft; R.D.S.G.C.: methodology, data curation, visualization, supervision; A.F.V.P.: data curation, visualization, writing-reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

## Data Availability Statement

Not applicable.

## Conflicts of Interest

The authors declare no conflict of interest.

## Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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