INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO
MESTRADO EM ENGENHARIA MECÂNICA

DESENVOLVIMENTO DE EQUIPAMENTO DE MANIPULAÇÃO DE OBJECTOS DEFORMÁVEIS E A SUA INTERACÇÃO COM UMA MÁQUINA DE INJECÇÃO DE PLÁSTICOS

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julho de 2023

POLITÉCNICO
DO PORTO

DEVELOPMENT OF EQUIPMENT FOR HANDLING DEFORMABLE OBJECTS AND ITS INTERACTION WITH A PLASTIC INJECTION MACHINE

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Dissertation presented to School of Engineering to fulfill the requirements necessary to obtain a Master's degree in Mechanical Engineering, carried out under the guidance of Doctor Adriano A. Santos.

2022/2023

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ACKNOWLEDGEMENTS

I would like to extend my heartfelt gratitude to all those who have played a role in bringing this thesis to fruition. First and foremost, I would like to express my sincere appreciation to Doctor Adriano Santos from the Instituto Superior de Engenharia do Porto for accepting the responsibility of guiding me throughout this journey. Despite the various challenges and setbacks encountered during the project, Doctor Adriano has consistently demonstrated understanding, patience, and unwavering support. His expertise and positive demeanor have been invaluable in overcoming the most demanding moments.

I am deeply grateful to Engineer Francisco Ferreira, my supervisor at Ficocables and Director of the Department of Continuous Improvement. Without his unwavering support and providing the subject matter for this work, this thesis would not have been possible. I am indebted to him for sharing his extensive technical knowledge of processes, products, and associated risks. His insights and ideas have been instrumental in the development of this project.

I would also like to express my appreciation to Engineer Mário Cardoso, Director of the Maintenance Department, for his invaluable support and expertise. His guidance has been essential in understanding the significant risks associated with the various solutions explored.

I extend my gratitude to my boss, Engineer Marco Carneiro, Ficocables Quality Director, for his continuous support throughout this project. His concern, availability, and flexibility have been a constant through the hole project.

To my family, I am deeply thankful for their unwavering support, particularly my parents, whose patience and encouragement have been instrumental in completing this project.

Lastly, I extend my heartfelt thanks to my friends, whose support, wise counsel, and enjoyable moments of leisure have undoubtedly enriched this entire process.

ABSTRACT

In this project, our objective was to thoroughly investigate the feasibility of automating a process at Ficocables by integrating a robotic arm. Specifically, we focused on automating the joining of two separate processes while eliminating the need for manual intervention in the second operation. The equipment involved in the process includes a Roboco Zamak injection machine and a Babyplast polymer injection machine. With well-defined project requirements, we explored various solutions and sought guidance from Fluidotronica, a renowned expert in this domain. With their support, we identified the collaborative robot JAKA Zu 3s, equipped with a long-finger gripper, as the optimal solution for our needs. To assess the financial viability, we conducted a meticulous financial analysis using methods like NPV and payback period, both of which demonstrated promising results. Although the implementation of the robotic arm is still pending, the outcomes of our study highlight its remarkable versatility for future applications within Ficocables. This project exemplifies the potential advantages of automation and offers valuable insights for forthcoming initiatives in this field.

KEYWORDS

Semi Deformable Linear Objects; Wires; Manipulation; Robotic Arm; Automation.

RESUMO

Neste projeto, o objetivo era investigar exaustivamente a viabilidade de automatizar um processo na Ficocables através da integração de um braço robótico. Especificamente, concentrámo-nos em automatizar a junção de dois processos separados, eliminando a necessidade de intervenção manual na segunda operação. O equipamento envolvido no processo inclui uma máquina de injeção de Zamak, denominada Robocop e uma máquina de injeção de polímero denominada Babyplast. Com os requisitos de projeto bem definidos, explorámos várias soluções e procurámos orientação junto da Fluidotronica, um especialista de renome neste domínio. Com o seu apoio, identificámos o robô colaborativo JAKA Zu 3s, equipado com uma pinça de dedos longos como a solução ideal para as necessidades deste projeto. Para avaliar a viabilidade financeira, efetuou-se uma análise financeira meticulosa utilizando métodos como o NPV e o período de retorno do investimento, tendo ambos demonstrado resultados promissores. Embora a implementação do braço robótico ainda esteja pendente, os resultados do nosso estudo destacam a sua notável versatilidade para futuras aplicações na Ficocables. Este projeto exemplifica as vantagens potenciais da automatização e oferece uma visão valiosa para iniciativas futuras neste domínio.

PALAVRAS-CHAVE

Objetos Lineares Semi-Deformáveis; Cabos; Manipulação; Braço Róbotico; Automação.

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LIST OF ABBREVIATIONS

List of abbreviations

ISEP	Instituto Superior de Engenharia do Porto
P.Porto	Instituto Politécnico do Porto
VAR	Virtual Automation Robot
DLO	Deformable Linear Objects
SDLO	Semi Deformable Linear Objects
NPV	Net Present Value

1. INTRODUTION

This chapter will be focused on presenting a small overview of the project. First, will be presented the contextualization of the subject followed by the objectives. On the next 3 subchapter will be explained the adopted methodology, the report structure and finally will be presented the host company.

1.1. Contextualization

For most of the history of mankind humans have constantly tried to seek substitutes to perform their tasks, the reasons for this may range from philosophical, economic, social, and scientific [1, p.1].

The project aborded in this essay derivates from a necessity of industrial facilities automate the simple/repetitive tasks to keep competitive. This demand is generally moved by financial factors, an operator compared with a robotic system is a big expense for a company, since an operator needs a salary, health care, vacations, gets sick and suffer from tiredness, in the other hand a robotic system may be a big initial investment compared with a person, but, on the long run, it pays off, since it only needs maintenance to keep going.

To automate a task that requires physical movements we usually apply robotics. The term *robotics* was first introduced by Asimov as the science responsible to study robots [1, p.2]. According to Andrew J. Kurdila and Pinhas Ben-Tzvi the definition of a robotic system is: ''*A robotic system is a reprogrammable, computer-controlled mechanical system that may sense and react to attributes of its surroundings as it performs assigned tasks with some degree of autonomy''* [2, p.6].

1.2. Objectives

The current case objective is to implement a robotic arm to move a component from place A (packaging 1) to place B (over-molding equipment) and finally to place C (packaging 2), so it's a simple pick and place task with the constrains that we are dealing with a Semi Deformable Linear Object (SDLO), and the position of the rigid part must be taken accurately considering the 6 Degrees of Freedom (DoF) of the piece. Right know this process is performed by an operator.

In this specific case, we are talking of a low value product, and this simple task is only an intermediate process of many other prosses before the final product that will be delivered to the client is achieved. An operator in this type of conditions is a big expense to the company and represents a very significative percentage of the final value of the product. Another great reason, which can be interpreted in two ways for implementing a robotic arm is the human side. The first thing that comes to mind when a process is automated is unemployment, and that's a fact, if we have someone doing a task almost 8 hours a day, and we put a robotic arm doing the same task, and most of the times in a more efficient and precise way, we may not need that operator anymore. But, the other side of the coin tells a different story, this kind of work is very thankless for those who do it, it's true that they receive their income in the end of the month, but that's all. Doing this type of task requires very little thinking from the operator, and, from a personal development point of view it's very ungrateful. As most people know our brain must be exercised to stay healthy and efficient, and one of the biggest ways people do that is at work, by solving problems and making decisions, whether they are small or big they require thinking. As conclusion, no longer having humans doing this kind of work would be a long-term way of giving them the opportunity to perform higher value/satisfaction kinds of work.

1.3. Methodology

The investigation method used in this report will be abduction approach. This is a combination of the deductive and inductive approach, so, an improvement opportunity was defined that should be a better solution then the current one, the objective is to prove that the solution is feasible and effective.

1.4. Report Structure

The report begins by providing a brief overview of robotic manipulators and their components.

In a second step, some of the most common configurations of robotic arms currently available in the market will be addressed. Next, we will present real cases of automation or semi-automation of processes that involve the manipulation of deformable or semi-deformable objects. Finally, the most relevant conclusions drawn from the bibliography will be presented.

1.5. Host Company

Ficocables shown in Figure 1 is a subsidiary of Ficosa International, based in Maia Portugal. It specializes in the research, development, production, and sales of systems and components for the automotive industry. The company has a long history, it was established in 1971 under the name Teledinâmica. In 1972, it merged with the company Pujol e Tarrago, and in 1993, the company name was changed to Ficocables. The current systems and components supplied by Ficocables reach three main areas. First, there are the motion transmission cables that range from door cables, hood cables, seat cable, brake cables and more. Second, the company is a supplier of comfort systems for seats. Last, the company has started the development of shifters.

Figure 1- Ficocables Instalations

2. STATE OF THE ART

In this chapter, the literature review will be presented regarding the theoretical issues that will be necessary for the practical development of the project. For this, several scientific articles and books were consulted. First will be presented a small introduction to robotic as an all, after this the report will be more focused in robotic manipulators. Keeping with the theme of robotic manipulators, some of the most common configurations of robotic manipulators on the market will be presented. The report will then provide real-world examples of automation or semi-automation in processes that involve manipulating Deformable Linear Objects (DLO) or SDLOs. Lastly, it will summarize the key findings and conclusions from the research literature.

2.1. Robotics definition

The definition of the term ‘’Robotics’’ has change through the years, and even today we can find different interpretations of the term.

Generally, the core of robotics implies the intersection of mechanical, electronics, signal processing, control engineering, computing, and mathematical modelling [2, p.5].

Thus, a robotic system usually consists of the following components [2, p.2–3]:

- Actuators – exercise the function of source of motion for the system (can be considered as the ''muscles'' of the robot), the source of power for this actuator is commonly electrical, pneumatical or hydraulic.
- Communicator - allow remote access to the robotic system, for this reason they can serve as transmitters or receivers of information.
- Control Unit – serves as the processing unit of the equipment, this can consist of a single processor or a central computer controlling various processors.
- End effector – servers as the link between the robotic system and the environment, this is an essential component that allow the robot to interact with is surroundings (can be considered as the ‘’hand’’ of the robot), a single robot can have more than one end effector.
- Sensors – has the function of collecting information from the environment outside the robot, normally they receive physical inputs and output electrical signal to be processed by the control unit.
- Power supply – server as a power supplier, this can be achieved by batteries or fixed power supplies, the second one is must commonly saw in high energetic demand systems.

Asimov, mentioned previously, also formulated the "Three Laws of Robotics" as a set of rules that all robots in his stories had to follow. The first law states that a robot may not injure a human being or, through inaction, allow a human being to come to harm. The second law states that a robot must obey the orders given by human beings, except when such orders would conflict with the first law. The third law states that a robot must protect its own existence, as long as such protection does not conflict with the first or second law. These laws are intended to ensure that robots behave ethically and do not harm humans [1, p. 2].

2.2. Robotic manipulator characteristics

This chapter will serve as an introduction to the various types of robotic manipulator available today, it is important to emphasize that we first approached robots in a more general way, but this chapter will specify the subject to robotic manipulator, being this the theme of this dissertation.

2.2.1. Mobility

Regarding mobility attributes robots may be classified as fixed or mobile robots, within mobile robots we can find wheeled, tracked, legged or undulating robots. In the modern industry of automation, the largest class in use are fixed robots, this are indicated to work in structured/controlled environments. In the future the use of mobile robots is very likely to increase, due to their versatility they are more capable to perform more complex tasks in unstructured environments. [1, pp.vii–viii]

2.2.2. Motion Characteristics

The motion characteristics of a robot can be planar or spatial.

Planar manipulators perform movements where all the moving links move parallel to each other, in other words all the positions of the end effector are contained in a planar surface. [2, pp.11–12]

Spatial manipulators are like planar manipulator with the exception that at least one of the joints must have spatial motion, in contrast to a planar manipulator we need a 3D model to represent all the possible positions of the end effector. [2, pp.11–12]

2.2.3. Degrees of freedom

The Degrees of Freedom (DoF) of a robotic arm refer to the number of ways in which the arm can move and the number of axes of movement it has.

The DoF of a robotic arm is typically determined by the number of joints it has and the type of motion each joint allows (examples of joints and their respective DoFs are shown in Figure 2). For example, a robotic arm with three joints that can each rotate around a single axis has 3 DoF. A robotic arm with four joints that can each rotate around two axes has 6 DoF, and so on. [2, p.12]

Overall, the degrees of freedom of a robotic arm play a key role in its versatility and ability to perform a wide range of tasks. They also determine the complexity and cost of the arm, with more DoF typically resulting in a more expensive and complex system.

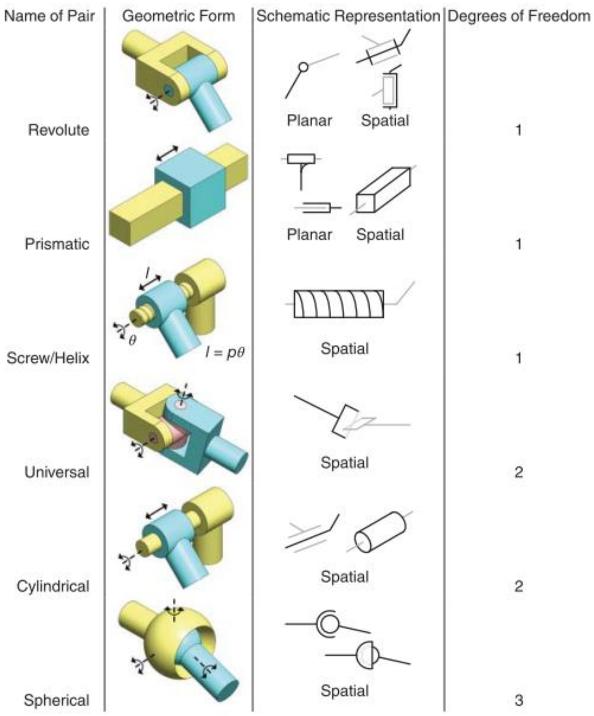


Figure 2- Ideal joints and their properties [2, p.9]

2.2.4. Driver Technology and drive Power

According to Kurdila [2, p.11] robots can also be characterized regarding their driving power:

- Electric robots – this use DC servo motor or stepper motors. Have the advantage of being clean and easy to control. [2, p.12]
- Hydraulic robot – as the name suggests they use hydraulic systems. Have the advantage of keeping up with high load tasks but require high maintenance due to fluid leaks and fluid compressibility problems. [2, p.12]
- Pneumatic robots – this use compressed air as their driving power. Are commonly applied in high-speed operations. This type of robot has the advantage of being clean but present challenges associated with air compressibility. [2, p.12]
- Direct drive manipulator – in this case every joint in the mechanism is drive by an actuator, in other words no torque transmission mechanism is used. This type is usually bulky and heavy. [2, p.12]
- Conventional manipulator – this type of manipulator generates torque that is magnified by a transmission mechanism, these is usually achieved via gear reduction or harmonic drive units. This type of design is usually more compact due to the possibility of using smaller actuators. [2, p.12]

2.2.5. Kinematic structure

The kinematic structure of a robotic arm refers to the arrangement of the joints and links that make up the arm and how they are connected to one another. The kinematic structure determines the range of motion and the degrees of freedom of the arm, as well as the mechanical properties and performance of the arm. [2, p.12–14]

A robotic arm typically consists of a series of links, connected by joints that allow for motion. The links can be solid or hollow and may be made of materials such as aluminum, steel, or composite materials. The joints can be rotary (hinge) joints, prismatic (sliding) joints, or more complex joints such as ball joints.

The kinematic structure of a robotic arm can be either serial or parallel. A serial kinematic structure consists of a series of links that are connected in a linear fashion, with each link connected to the next through a single joint. A parallel kinematic structure consists of a series of links that are connected in a non-linear fashion, with each link connected to the base and the end effector through multiple joints.

The kinematic structure of a robotic arm plays a crucial role in its performance and capabilities. It determines the range of motion, the degrees of freedom, and the mechanical properties of the arm, and it affects the accuracy, speed, and payload capacity of the arm.

2.2.6. Workspace Geometry

The workspace geometry of a robotic arm can be visualized as a volume in space, within which the arm can reach and manipulate objects. The size and shape of this volume depend on the length of the arm and the range of motion of its joints. A longer arm or a joint with a greater range of motion will have a larger workspace geometry, while a shorter arm or a joint with a limited range of motion will have a smaller workspace geometry. [2, p.14]

2.3. Examples of robotic arms configurations

This chapter servers as an introduction to some of the most common robotic arm’s variants. These will be approached in a linear way focusing on presenting their most common applications and the main advantages and disadvantages. It is important to point out that not all the possible classifications of robotic manipulators will be presented, since they vary from author to author and would make this chapter too long for the objective of this assignment.

2.3.1. Cartesian robotic arms

Cartesian robotic arms, shown in Figure 3, are a type of robotic arm that is based on a Cartesian coordinate system, depending on its use they are commonly referred as gantry or traverse robotic arms. Gantry robotic arms are normally suspended and used for moving heavy loads in an industrial facility, while traverse arms are most applied for higher precision tasks such as surgical operations and optical experiments. [2, p.15–16]

Figure 3- Sepro S5 Line [3]

The Cartesian coordinate system is a system of three mutually perpendicular axes (x, y, and z) that are used to specify the position of a point in space. in a Cartesian robotic arm, each joint is connected to the previous joint by a linear actuator, which allows the arm to move in a straight line along one of the three Cartesian axes. The arm consists of three or more joints, with each joint corresponding to one of the axes in the Cartesian coordinate system.

The primary advantage of Cartesian robotic arms is their simplicity and ease of use. They are straightforward to program and control, as the motion of the arm is directly related to the position of the joints along the Cartesian axes. This makes them well suited for tasks that require precise, linear motion, such as pick and place operations and assembly tasks. However, Cartesian robotic arms are limited in their range of motion and are not as versatile as other types of robotic arms. They are generally not suitable for tasks that require more complex or non-linear motion, such as welding or painting.

Overall, Cartesian robotic arms are a simple and reliable option for tasks that require precise, linear motion and are well suited for applications in manufacturing, assembly, and material handling.

2.3.2. Cylindric robotic manipulator

A cylindrical robotic manipulator shown in Figure 4 is a type of robotic arm that is based on a cylindrical coordinate system. The cylindrical coordinate system is a system of three coordinates (r, θ, z) that are used to specify the position of a point in space. The r coordinate represents the distance from the origin to the point along a line perpendicular to the z-axis, the θ coordinate represents the angle between the x-axis and the line connecting the origin to the point, and the z coordinate represents the distance from the origin along the z-axis. [2, p.16]

In a cylindrical robotic manipulator, each joint is connected to the previous joint by a rotary actuator, which allows the arm to rotate around the z-axis. The arm consists of two or more joints, with each joint corresponding to one of the coordinates in the cylindrical coordinate system.

Cylindrical robotic manipulators are well suited for tasks that require precise, circular motion, such as assembly tasks, pick and place operations, and material handling. They are also well suited for tasks that require a large range of motion, as they can reach points that are further away from the base of the manipulator than other types of robotic arms.

However, cylindrical robotic manipulators are limited in their ability to perform tasks that require more complex or non-linear motion, such as welding or painting. They are also generally more complex and expensive to build and operate than other types of robotic arms, such as Cartesian or spherical manipulators.

Overall, cylindrical robotic manipulators are a reliable and versatile option for tasks that require precise, circular motion and are well suited for applications in manufacturing, assembly, and material handling.

Figure 4- ST Robotics R19E 4-axis robot arm [4]

2.3.3. Spherical Robotic Manipulator

A spherical robotic manipulator shown in Figure 5 is a type of robotic arm that is based on a spherical coordinate system. The spherical coordinate system is a system of three coordinates (r, θ, ɸ) that are used to specify the position of a point in space. The r coordinate represents the distance from the origin to the point, the θ coordinate represents the angle between the x-axis and the line connecting the origin to the point, and the ɸ coordinate represents the angle between the z-axis and the line connecting the origin to the point. [2, p.17–18]

In a spherical robotic manipulator, each joint is connected to the previous joint by a rotary actuator, which allows the arm to rotate around the z-axis or the y-axis. The arm consists of three or more joints, with each joint corresponding to one of the coordinates in the spherical coordinate system.

Spherical robotic manipulators are well suited for tasks that require spherical motion and larger ranges of motion, as they can reach points that are further away from the base of the manipulator than other types of robotic arms. The most common applications of spherical robotic arms are welding or painting, being that these are tasks that generally do not require as much precision as pick and place operations. One disadvantage of this type of robotic manipulator is that their kinematics and dynamics when compared with cartesian or cylindrical manipulators are more complicated and complex.

Figure 5- Kawasaki-Unimate 2000 [5]

2.3.4. SCARA Robotic Manipulator

SCARA (Selective Compliance Assembly Robot Arm) shown in Figure 6 is a type of robotic manipulator that is designed for use in assembly tasks. SCARA manipulators are characterized by their two parallel rotary joints, which allow the arm to move in a plane perpendicular to the base of the manipulator. [2, p.16–17]

The primary advantage of SCARA manipulators is their high-speed and high-precision performance, which makes them well suited for tasks such as assembly, pick and place, and material handling. They are also relatively simple and easy to program, as the motion of the arm is directly related to the position of the joints. SCARA manipulators typically have a limited range of motion and are not as versatile as other types of robotic arms, such as cylindrical or spherical manipulators. They are generally not suitable for tasks that require more complex or non-linear motion, such as welding or painting.

Overall, SCARA manipulators are a reliable and efficient option for tasks that require high-speed and high-precision motion and are well suited for applications in manufacturing, assembly, and material handling.

Figure 6- Epson G-Series SCARA Robots [6]

2.3.5. PUMA Robotic Manipulator

PUMA (Programmable Universal Machine for Assembly) is a type of robotic manipulator that is designed for use in assembly tasks. [2, p.18]

The primary advantage of PUMA manipulators is their versatility and ability to perform a wide range of tasks, including assembly, pick and place, material handling, and welding. They are also relatively simple and easy to program, as the motion of the arm is directly related to the position of the joints. PUMA manipulators have a large range of motion and are well suited for tasks that require complex or non-linear motion. However, they may be more complex and expensive to build and operate than other types of robotic arms, such as Cartesian or SCARA manipulators.

Overall, PUMA manipulators, shown in Figure 7 are a reliable and versatile option for tasks that require a wide range of motion and are well suited for applications in manufacturing, assembly, and material handling.

Figure 7 - Puma 500 [7]

2.4. Review of similar projects

2.4.1. Industry 4.0: examples of the robotic arm for digital manufacturing processes

This paper studies the application of the KUKA KR16 to 3 distinct operations, milling, Styrofoam cutting and pick and place, the author also presents all modifications that must be performed to achieve the objective. [8]

For this report we will focused on the Pick and Place operation, being the one more like the project on demand.

The KUKA KR16 is a general-purpose robot arm, usually used for medium weight operation, is biggest advantages are speed and accuracy.

The control unit chosen is KUKA KRC 4 that presents the following characteristics:

- Optional KUKA.CNC control – with this additional feature the robot can be programed and operated directly via G-code.
- Optional High end PLC support – with this feature is possible to have full access to the entire controller Input/Outputs (I/O) system.
- Fully integrated safety controller – designed to prevent accidents, injuries, and other adverse events by detecting hazardous conditions and taking appropriate action to mitigate or eliminate the risk.

For the pick and place operation the following features were added:

- Suction toll – ability to pick up different size and geometry objects.
- Solenoid valve – an electrically controlled valve for fluid controls like shutting, release, distribution, dosage or mixing of fluids)
- Vacuum pump (convert the compressed air blow into suction)
- Camera

To control the robot was originally used the KUKA Robot Controller (KRC) that works with KUKA Robot Language (KRL). To make the connection between the Robot Operation System (ROS) and the robot, the author used a KUKAVARPROXY that works as a server in the KRC. The ROS system communicates locally with the user program and remotely with the KUKAVARPROXY server via Transmission Control Protocol (TCP) / Internet Protocol (IP). The KUKAROS Open Communication package was used to make the ROS communication with the KUKAVARPROXY. To make the ROS communication with KUKAVARPROXY the author integrates the KUKAROS Open Communication package. The schematic presentation of the system is shown in Figure 8.

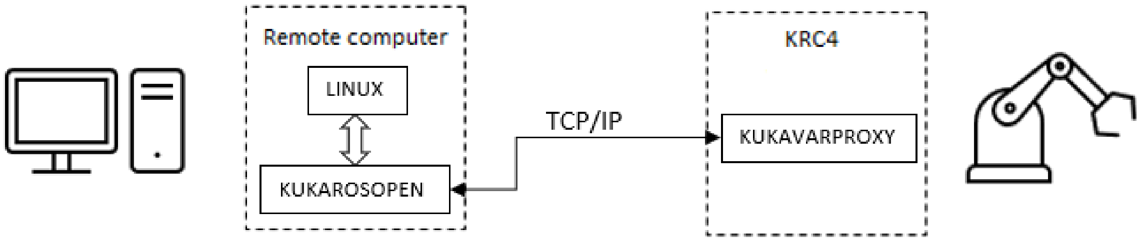


Figure 8- KUKA-ROS communication

In the final discussion of the paper the author presents the biggest challenges and results of the application. The biggest challenges were the preparation and activation of the suction tool, the identification of the position and orientation of the part and defining movement strategies. As results the author concluded that the application was effective and works in concordance with the Industry 4.0 improving manufacturing interaction and customization.

2.4.2. Mechatronic Re-Design of a Manual Assembly Workstation into a Collaborative One for Wire Harness Assemblies

This article describes the process of redesigning a manual assembly workstation for wire harness assemblies into a collaborative one using mechatronic principles. The goal of the redesign was to improve the efficiency and safety of the assembly process by introducing automation and robotics. [9]

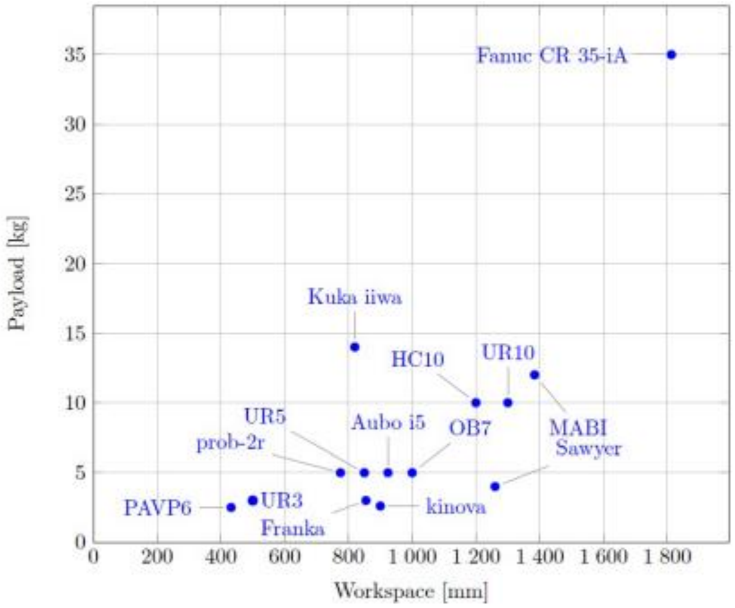
The process of developing the new collaborative workstation follow the Good Engineering Practice (GEP), which consist of following stages:

1) Problem definition
2) Background research
3) Requirements specifications
4) Conceptual design
5) Detailed design
6) Assessment of requirements satisfaction

The author of this article emphasis a lot on the ergonomics studies of the workstation, considering that the work to be developed is more focused in integrate a robotic arm that will only need to work alongside the operator for the feeding of the initial product and packaging of the final product, so the present work will be focused on the integration process and results of the robotic arm.

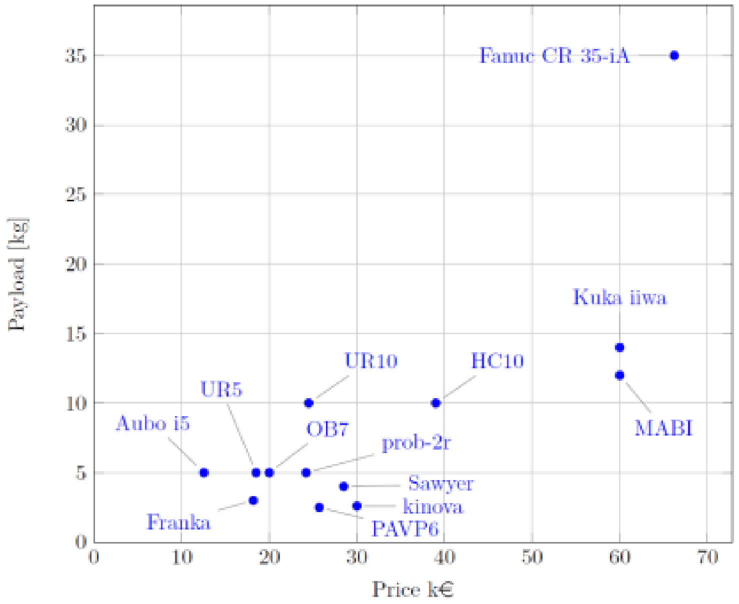
The placement of the robot was an important factor in the selection process, as it was decided that the robot and operator should not work on the same side of the assembly panels for safety reasons. The robot was placed at the back of the workstation, with the worker and robot operating on opposite sides of the assembling panels. The robot was selected based on its reach and payload, as well as its price.

After conducting market research, the author builds to different graphics comparing the Payload versus Workspace (Figure 9) and Payload vs Price (Figure 10), after analysis the authors selected the Universal Robots UR 10, which has a reach of 1300 mm and a payload of 10 kg and is suitable for both assembly and workbench tasks. The UR10 was integrated into the workstation with a steel base, and the robot controller unit was housed in an internal compartment in the bench.



(a) Payload vs. workspace

Figure 9- Relation between Payload and Workspace [9]



(b) Payload vs. price

Figure 10- Relation between Payload and. Prices [9]

To perform the taping operations the author [9] assembled a Kabatec KTH Spot 9 as an end effector. The taping pistol was mechanically and electrically connected to the robot and all the command and monitoring signals available in the control logic of the pistol were managed by an ad-hoc board This allowed the robot to directly activate and monitor the pistol.

The authors describe a problem that arose when the collaborative robot was placed at the back of the workstation and the taping pistol's approach direction to the wires was inverted. This caused the pistol to push the wires out of the jigs rather than taping them together. To solve this problem, the authors designed a wire locking system that allowed the operator to insert the wires into the jigs and kept them in place while the robot worked on them.

Finally in order prevent future incidents the author identified three areas with different conditions of human-robot interaction and potential hazards [9]: the human area, the robot area, and the shared area. Taking this into account the author identifies three possible hazards (H#).

H1 – If an operator enters the area where the robot is operating without proper authorization, there is a risk of an impact or collision with the robot parts or getting trapped between the robot and the workstation. This could potentially affect all parts of the human body.

H2 – There is a potential hazard in the shared area of the workstation where the human and robot are interacting. The presence of body parts in this area could potentially result in injuries especially in the hands and fingers of the operator.

H3 – If an operator places their body parts in the space between the two panels while the robot is moving, there is a risk of an impact between the robot parts and the operator's lower arms, wrist joints, and hands/fingers. This risk is especially relevant during the motion of the robot between the two panels.

To prevent this hazard's, the author implemented six safety measures (SM#).

SM1 – Introduction of physical and optical guarding around the robot operation zone to avoid unauthorized entries.

SM2 – Elimination of sharp edges.

SM3 – Introduction of dual-hand commands to force the operator to move the hands to the second panel during the taping operation.

SM4 – Programming the robot trajectories to prevent hazards.

SM5 – Implementation of audio and visual signal to communicate the motion and state of the arm.

SM6 – Provide training to the operators.

In the end the author presented the results of the application, the most significant improvement was a reduction in cycle time per harness from 40 seconds to 35 seconds. This resulted in a 12.3% reduction in cycle time and a productivity increase that could lead to a payback period of less than 1.5 years for the company, considering a 55000€ investment for the final workstation version.

2.4.3. Robotized Assembly of a Wire Harness in a Car Production Line

This research focuses on using multiple robot arms in the assembly of flexible parts, specifically wire harnesses in an automotive plant. The goal is to automate a process that is currently performed by skilled workers and is challenging to automate. The developed robot system is designed to assemble complex, deformable objects, such as wire harnesses, in a way that simulates real-world conditions. The research aims to explore the feasibility and potential of using robots for assembly tasks involving flexible parts in industrial settings. [10]

They demonstrate the feasibility of this approach through the implementation of a prototype system and experimental validation. The main challenges in automating this process are related to the difficulties in measuring and manipulating the state of the wire harnesses, which have complex physical properties including both elastic and plastic deformation, as well as segments with different diameters. The authors propose a solution for practical implementation in automobile plants, with the goal of contributing to the exploration of the feasibility and potential of robotized assembly using deformable parts in actual plants.

The assembly process chosen for this study involves attaching the wire harness to an instrument panel frame in the front of a car. The wire harness has a tree-like structure with branches that are connected to different instruments. The robot system applied can be saw in Figure 11 and consists of three robot arms with 1-DoF grippers mounted on the end effectors.

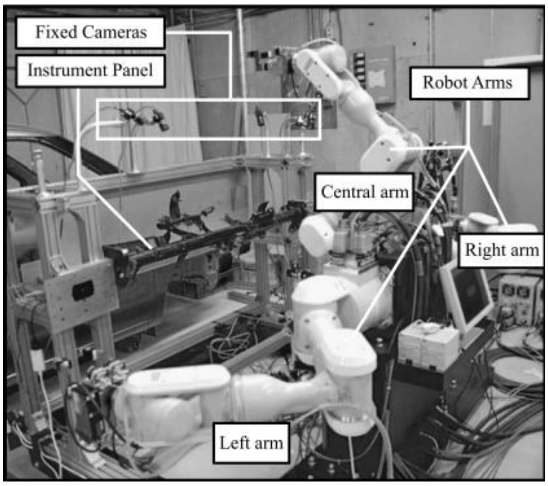


Figure 11 - Prototype Robot System [10]

The grippers can be used for mating by inserting their toes into holes or for gripping wire segments by clipping them between the arms of the gripper. The end effectors shown in Figure 12 also have two cameras and a laser range sensor, and there are an additional 10 cameras fixed around the work cell to provide information for recognizing the target clamp.

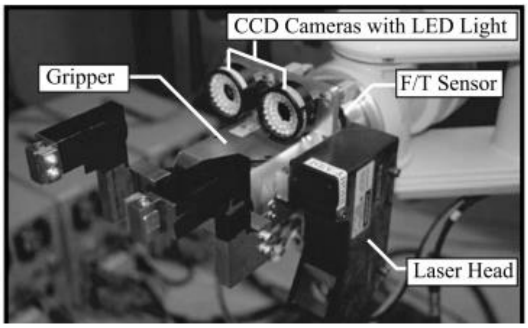


Figure 12 - Closed up view of the End-Effector [10]

The prototype system also uses specially designed plastic covers presented in Figure 13 with markers attached to each clamp to simplify the recognition, relative position, and manipulation of the wire harness.

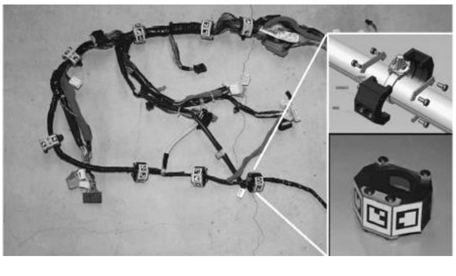


Figure 13 - Clamp cover attached with markers for recognition [10]

In this paper methodologies and solutions are presented for problems related to the cooperation between the 3 robot arms, always considering the elastic and plastic limits of the cables, this section will be omitted because it is not relevant to the present work.

As conclusion the authors of this study consider the assembly process was successful, with an average assembly time of 3 minutes and a success rate of 50%. The main issues that led to experiment failures were the lack of robustness in vision and laser processing, and the deformable properties of the wire harness, which limited the ability to adjust the torsional state of the wire segments.

2.4.4. A Practical Solution to Deformable Linear Object Manipulation: A Case Study on Cable Harness Connection

This paper discusses the challenges and potential solutions for manipulating DLOs in the context of flexible automation in industries such as electronics and automotive manufacturing. DLOs, such as cable harnesses, have a high number of degrees of freedom and are difficult to model and control, making it difficult to apply traditional methods for manipulating rigid objects. The paper discusses approaches for modeling DLOs, including physically based methods that use the physical characteristics of the object and learning-based methods that use observed data. The paper also discusses the use of visual sensors and machine vision algorithms for estimating the state of DLOs. The focus of the paper is on a particular type of DLO called a semi-deformable linear object (SDLO), which consists of both deformable and rigid parts, and the goal is to achieve accurate state estimation and operation at sub-millimeter accuracy. The paper discusses the potential for this solution to be applied in real industrial applications. [11]

SDLOs manipulation is a challenge because the pose of the rigid part becomes undetermined because of the attached deformable parts, and the initial pose of the SDLO's rigid part may be unreachable for the robot. The authors propose to use a dual-arm robot Figure 14 to solve these problems by estimating the state of the SDLO's rigid part and using the robot to perform a series of pose changes to reach the desired final pose. As a case study, the authors consider the task of connecting a cable harness to a socket, which requires accurately estimating the pose of the connector and aligning it with the socket with a tolerance of 0.8mm.

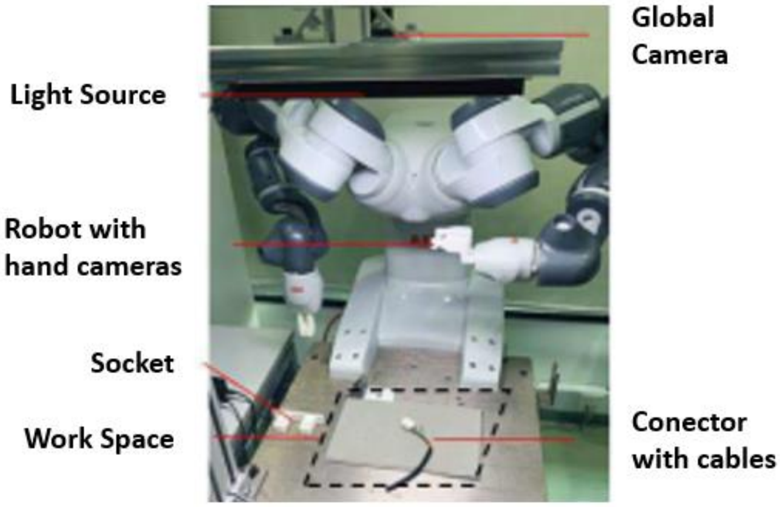


Figure 14 - Dual-Arm Robot [11]

To achieve the proposed objective the system setup consists of the following components:

- Fixed global camera
- Light Source
- Fixed socket
- Cable harness (SDLO sample shown in Figure 15)
- Dual-arm collaborative robot
    - One in-hand camera in each arm.

Figure 15 - SDLO Sample and corresponding socket [11]

The complete process is divided into two operations that are both also broken down into two sub-operations, these are described below.

1. **State Estimation of SDLO**
    a. Rough locating: The goal of the rough locating step is to detect the presence of a connector in the workspace and to approximate its position. This is done using a deep learning-based object detection method called MobileNet-SSD. A set of 550 images of the cable harness were used to train and test the object detection neural network, with 98.5% accuracy and an average time consumption of 0.3 seconds. The rough location of the connector is provided as a pixel coordinate in the camera frame, which outlines the connector in the Figure 16. While this rough location is not accurate enough for further operations, it is useful for narrowing the region of interest for the next step, which is fine positioning of the connector.

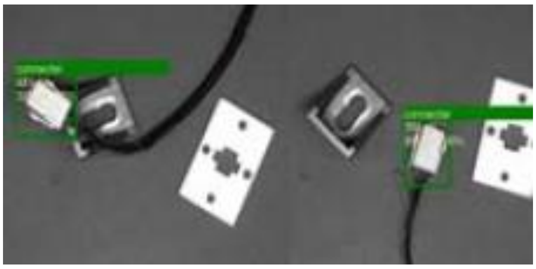


Figure 16 - Rough Locating Results [11]

    b. Fine positioning: Fine positioning uses a shape-based 3D matching method to obtain the accurate 6-DoF pose Figure 17 of the SDLO's rigid part, by matching a 2D image to a set of 2D shape representatives generated from a 3D CAD model of the object. The result of this method is presented in Figure 18. The authors conducted experiments to evaluate the repeatability of the fine positioning method and found that it had a maximum translation error of 0.645 mm with an average of 0.316 mm and a maximum rotation error of 0.391 degrees with an average rotation error of

0.211 degrees. These results were sufficient for the task of connecting a cable harness to a socket with a tolerance of 0.8 mm.

Figure 17 – Fine Position Results [11]

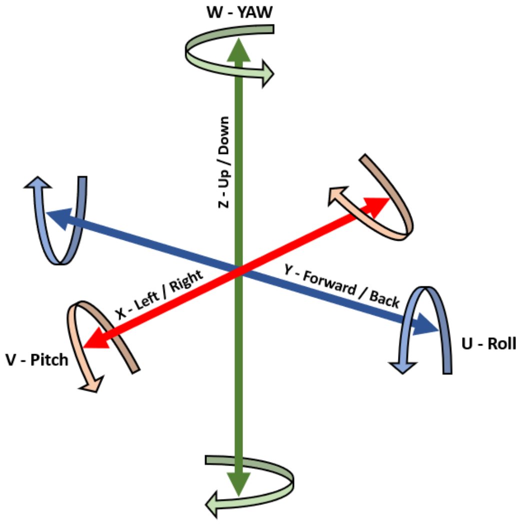


Figure 18 - 6-DoF Pose Parameters

2. Picking and plugging operation

a. Task planning: The left gripper is designed with locating features on the fingers and has a specific final approaching and picking position. However, in some cases the initial position of the connector may make it difficult or impossible for the left gripper to reach the picking position. In this case, the robot can use the right gripper to adjust the pose of the connector, rotating it to a position that is reachable by the left gripper. A set of hand changing function modules have been defined in advance to handle a variety of initial connector poses. The task planning for the robot involves generating a finite number of operation instructions that will allow the robot to successfully connect the cable harness to the socket. An example of a non-hand-changing operation and hand changing operation is shown in Figure 19.

b. Operation: The overall success rate of these trials was 26 out of 30. The failure cases occurred when the connector was already out of the working range of the robot, which means that it was too far away from the robot for it to be able to reach and pick it up.

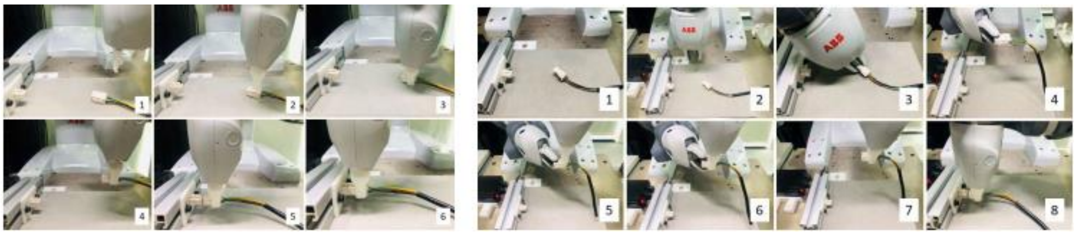


Figure 19- Non-hand-changing operation (left) and hand-changing operation (right) [11]

In summary, the proposed method for manipulating semi-deformable linear objects in this study involves using a learning-based object detection approach to rough locate the position of the rigid part of the SDLO and a shape-based matching algorithm to accurately determine its 3D pose. Based on the 3D pose of the connector, the appropriate operation strategy (either hand-changing or non-hand-changing) is selected to achieve successful manipulation of the SDLO, in this case, a harness-socket connection. The method was tested and found to be practically feasible for industrial applications, with an average error of 0.316mm for translational DoFs and 0.211 degrees for rotational DoFs in the 3D pose determination. In a verification test using a dual-arm robot, the proposed solution had a success rate of 26 out of 30 trials. The failures occurred when the connector was already out of the working range of the robot.

2.4.5. Robotic Wires Manipulation for Switchgear Cabling and Wiring Harness Manufacturing

This paper focuses on the routing of DLOs by analyzing the generation of feasible trajectories based on the desired path and environmental constraints and obstacles, including points that must be used to fix the DLO in place using clamps or other means. The robot must also ensure proper tension of the cable to prevent damage or deviation from the desired path.

The problem is addressed by designing a Cyber-Physical System (CPS) shown in Figure 20 comprising a 7-DoFs Panda from Franka Emika equipped with a Schunk PG70 industrial gripper with tactile sensors. The use of tactile sensors allows the robot to perceive objects within its gripper, which is important for tasks involving deformable objects. The sensors also provide information that can be used to constantly monitor the manipulation process and detect and diagnose faults. In addition, the gripper has a cable tension control system that helps to maintain the desired traction force on the cable and prevent damage to components. The software used is based ROS and motion planner used is MoveIt™! Wich includes many motion planning algorithms from the Open Motion Planning Library. [12]

The proposed control and perception system (CPS) was tested on a laboratory test bench and was able to successfully complete the desired task.

Figure 20- The cyber-physical system for cable manipulation composed by a robotic arm, a parallel industrial gripper and a pair of tactile sensors [12]

3. DEVELOPMENT

In the development chapter of this project, we delve into the crucial aspects of requirement specification, expert consultation, arm selection, and financial analysis. Our objective is to outline the comprehensive process undertaken to identify and address the needs of the project. Starting with a clear definition of project requirements, we establish the foundation for selecting an appropriate robotic arm solution. In order to make informed decisions, we sought guidance from Fluidotronica, a renowned company specializing in robotic arms. With their expert advice, we carefully considered various factors to determine the most suitable arm for our application. Additionally, we conducted a thorough financial analysis, employing methods such as NPV and Payback Period Analysis, to assess the economic viability and potential returns on investment. This chapter provides a detailed account of our methodology and the steps taken to ensure the successful development and financial evaluation of the project.

3.1. Detailed Specifications of the Operation

This section, will begin by presenting the technical details of the operation to be performed. The specification of the operation can be categorized into three types, each with varying degrees of flexibility and potential for modification:

1. Unchangeable Specifications: These specifications represent fixed limitations that cannot be altered under any circumstances. They form the foundational parameters upon which the entire operation is based, and any deviation from these constraints would be impractical or infeasible.

2. Specifications with Some Flexibility: This category includes specifications that allow for minor modifications if necessary. However, it is crucial to carefully evaluate the advantages and disadvantages of any proposed changes to ensure they align with the overall objectives of the project. Considerations such as resource allocation and the potential impact on the final operation or product must be taken into account before implementing any alterations.

3. Specifications that Can Be Modified: These specifications are initially defined but have the potential to be changed without significant repercussions on the company's resources or the operation/product being realized. The flexibility in modifying these specifications allows for adjustments to be made based on evolving requirements, technological advancements, or other relevant factors. However, any modifications should still be evaluated to ensure they do not compromise the overall effectiveness and efficiency of the automated process.

By categorizing the specifications in this manner, is possible to establish a clear framework for analyzing the requirements of the operation and make informed decisions throughout the implementation process.

3.1.1. Unchangeable Specifications

- Health and Safety Guidelines: The operation must strictly adhere to established safety guidelines to ensure the well-being of workers. This includes the implementation of mandatory safety features such as emergency stop buttons, collision detection systems, and force-limiting mechanisms. These measures are essential to prevent accidents and maintain a safe working environment.

- Maintenance Requirements: The robotic arm must be designed to facilitate regular maintenance activities without causing disruptions to the overall production process. This involves providing convenient access to the arm and other integrated equipment, allowing maintenance personnel to carry out necessary inspections, lubrication, and repairs efficiently. Implementing proper maintenance protocols ensures the longevity and optimal performance of the robotic arm.
- Tolerances: The robotic arm must operate within strict tolerance limits to maintain high-quality standards in the operation and the final product. To prevent any detrimental effects on product quality, the robotic arm must work with a minimum tolerance of 0.1 mm. This ensures precise and accurate movements, minimizing errors and deviations in the operation's outcomes.

By incorporating these unchangeable specifications, the robotic arm operation can prioritize the safety of workers, maintain efficient maintenance practices, and uphold stringent quality requirements.

3.1.2. Specifications with Some Flexibility

- Production Capacity: The operation should align with the plant's existing production capacity to avoid resource and infrastructure strain. However, in certain cases, minor adjustments to the first injection equipment may be allowed if they result in overall performance improvement. The target capacity is set at 800 pieces per hour, with the capability to handle 2 pieces at a time.
    - ➢ Target Capacity: 800 pieces per hour, 2 pieces at a time.
- Reach Limitations: The robotic arm's reach is limited by the possible layouts and entry spaces of the other integrated equipment in the operation. However, slight adjustments to the reach limitations can be made to accommodate specific requirements.
    - ➢ Working Radius Range: 0.5 meters to 1 meter
- Payload Capacity: The robot arm must have the ability to work with a certain minimum payload without compromising the operation's result. This includes accounting for the weight of the product to be moved, as well as the weight of the gripper and any additional components such as sensors or cameras. While the weight of the product remains unchangeable, modifications can be made to the number of cable end fittings picked up at once, and optimization or modification of the gripper and associated components is also allowed.
    - ➢ Product Weight: 20g (to be confirmed)
    - ➢ Gripper and Associated Components: ±500g (to be confirmed)
- Timing Adjustments: The operation's timing sequence can be adjusted within defined limits to optimize production flow or accommodate changing requirements. This flexibility allows for the optimization of the arm's speed to ensure efficiency for different tasks or operational needs.
- Communication Protocols: The operation should support various communication protocols or interfaces to seamlessly integrate with existing plant systems, ensuring effective information exchange and coordination.

By incorporating these specifications with flexibility, the robotic arm operation can effectively adapt to varying production needs, optimize overall performance, and seamlessly integrate into the plant's existing systems.

3.1.3. Specifications that Can Be Modified

- Workflow Sequencing: The operation can be rearranged or sequenced within predefined constraints to optimize process flow. This flexibility allows for the optimization of the workflow by considering variables such as prepackaging operations, control areas, and the number of cable end fittings to be picked up at once. By fine-tuning the sequencing, the operation can achieve greater efficiency and productivity.
- Packaging Variations: The operation allows for the utilization of different packaging systems and formats. By accommodating various packaging variations, the operation can enhance its versatility and adaptability.
- Quantity of robot arms: The number of robotic arms to be applied can vary considerably, it may be more advantageous to use more economical and less complex arms for the project in question.

By incorporating these specifications that can be modified, the robotic arm operation gains the ability to optimize process flow and adapt to different packaging needs. This flexibility ensures efficient workflow sequencing and enables the integration of diverse packaging solutions, ultimately enhancing productivity and meeting customer requirements.

3.2. First Theorical Concepts

This chapter will delve into the theoretical solutions for the project at hand after defining its requirements and specifications. The solutions presented here offer different approaches to address the challenges identified.

The presented solutions exhibit variations primarily concerning the three parameters discussed in the previous subchapter, which remain the same throughout the analysis. These parameters are:

a) Workflow Sequencing: This parameter encompasses considerations related to prepackaging operations, control areas, and the number of cable end fittings picked up at once. Different solutions may involve adjustments in these aspects to optimize the sequencing of the workflow.
b) Packaging Variations: The parameter of packaging variations explores different options for packaging systems and formats. The solutions may include the implementation of diverse packaging approaches to accommodate specific product requirements or market demands.
c) Quantity of Robot Arms: The quantity of robot arms employed in the operation represents a significant factor. Solutions may involve the use of a single robot arm or multiple arms to accomplish the desired objectives efficiently.

By examining these parameters, the theoretical solutions aim to find optimal approaches that effectively address the project's requirements and specifications. Each solution's viability and potential benefits will be thoroughly analyzed in the subsequent chapters.

Additionally, the parameters described above have a substantial impact on several key requirements that have been previously discussed. These requirements include:

1. Production Capacity: The chosen solutions will significantly influence the production capacity of the operation. By optimizing workflow sequencing, packaging variations, and

the quantity of robot arms, the production capacity can be effectively increased or optimized.

2. Reach Limitations: The reach limitations of the robotic arm are directly affected by the selected solutions. Adjustments in workflow sequencing and packaging variations may impact the range of movements and accessibility of the robotic arm within the operation.
3. Payload Capacity: The theoretical solutions must carefully consider the payload capacity of the robotic arm. By optimizing the number of cable end fittings picked up at once and taking into account the weight of the gripper and associated components, the payload capacity can be effectively managed without compromising the operation.
4. Communication Protocols: The chosen solutions may necessitate adjustments to the communication protocols and interfaces used within the operation. Compatibility with existing plant systems and the ability to integrate seamlessly are crucial factors to ensure efficient and reliable communication.
5. Timing Adjustments: The timing sequence of the operation can be adjusted within certain limits to optimize production flow and accommodate changing requirements. Solutions may involve fine-tuning the speed and coordination of the robotic arm to enhance overall efficiency and productivity.

Considering these requirements and the impact of the described parameters, the theoretical solutions aim to address them effectively and ensure the successful implementation of the robotic arm automation within the plant operation.

In order to better understand the intricate relationships and interdependencies within the project, a detailed analysis of the correlations between the identified parameters and the associated requirements has been conducted. This exploration aims to shed light on the vital connections that exist between different aspects of the project's implementation. By examining these correlations, it becomes evident how specific parameters impact various requirements, ultimately guiding the development of effective and comprehensive solutions.

The parameters, namely Workflow Sequencing (Parameter A), Packaging Variations (Parameter B), and Quantity of Robot Arms (Parameter C), have been identified as crucial factors influencing the project's outcomes. These parameters encompass key considerations such as workflow optimization, packaging adaptability, and the optimal utilization of robotic arms. By delving deeper into these parameters and their correlations with specific requirements, a clearer picture emerges of how each aspect contributes to the overall success of the project.

The subsequent sections will provide an in-depth explanation of the correlations established between the parameters and the corresponding requirements. Specifically, the impact of Parameter A will be explored in relation to Requirement 1 (Production Capacity), Requirement 3 (Payload Capacity), Requirement 4 (Communication Protocols), and Requirement 5 (Timing Adjustments). Parameter B will be analyzed in conjunction with Requirement 1 (Production Capacity) and Requirement 2 (Reach Limitations), while Parameter C will be examined in relation to all five requirements.

By thoroughly understanding these correlations, project stakeholders can make informed decisions and devise appropriate strategies to ensure the successful implementation of the project. The insights gained from this analysis will serve as a valuable foundation for the subsequent stages of the project, allowing for the development of tailored solutions that address the specific requirements and specifications at hand.

1. Parameter A (Workflow Sequencing):

- Correlated with Requirement 1 (Production Capacity): Optimizing the workflow sequencing can have a direct impact on the production capacity of the operation. By efficiently organizing prepackaging operations, control areas, and the number of cable end fittings picked up at once, the overall production capacity can be enhanced.
- Correlated with Requirement 3 (Payload Capacity): The workflow sequencing directly influences the payload capacity of the robotic arm. By optimizing the sequencing, it becomes possible to manage the weight of the gripper and associated components, ensuring that the arm can handle the required payload without compromising the operation.
- Correlated with Requirement 4 (Communication Protocols): The chosen workflow sequencing may require adjustments to the communication protocols and interfaces used within the operation. Integration with existing plant systems and ensuring effective communication are essential aspects that need to be considered.
- Correlated with Requirement 5 (Timing Adjustments): Workflow sequencing plays a crucial role in timing adjustments. By optimizing the sequencing, the speed and coordination of the robotic arm can be adjusted to improve overall efficiency and productivity.

2. Parameter B (Packaging Variations):
    - Correlated with Requirement 1 (Production Capacity): By considering different packaging variations, it becomes possible to optimize the production capacity of the operation. Adapting the packaging systems and formats to meet specific requirements or market demands can enhance overall productivity.
    - Correlated with Requirement 2 (Reach Limitations): Packaging variations can impact the reach limitations of the robotic arm. Adjusting packaging systems and formats can affect the range of movements and accessibility of the arm within the operation.
3. Parameter C (Quantity of Robot Arms):
    - Correlated with Requirement 1 (Production Capacity): The quantity of robot arms used in the operation directly affects the production capacity. Deploying multiple robot arms can increase productivity and throughput, thereby enhancing the overall production capacity.
    - Correlated with Requirement 2 (Reach Limitations): The quantity of robot arms also impacts the reach limitations. Having multiple arms enables more flexibility in reaching different areas and performing tasks simultaneously.
    - Correlated with Requirement 3 (Payload Capacity): The quantity of robot arms influences the payload capacity. By considering the number of cable end fittings picked up at once and optimizing the weight of the gripper and associated components, the payload capacity can be effectively managed with multiple arms.
    - Correlated with Requirement 4 (Communication Protocols): The use of multiple robot arms may require adjustments to communication protocols and interfaces to ensure seamless integration with existing plant systems.

- Correlated with Requirement 5 (Timing Adjustments): Having multiple robot arms allows for more efficient timing adjustments. By coordinating the movements of the arms, the overall timing sequence can be optimized to improve operational efficiency.

By establishing these correlations, it becomes evident how each parameter directly influences multiple requirements. This understanding is essential for designing effective and comprehensive solutions that address the project's objectives and specifications. Bellow in Figure 21 it's presented a scheme of the corresponding correlations explained.

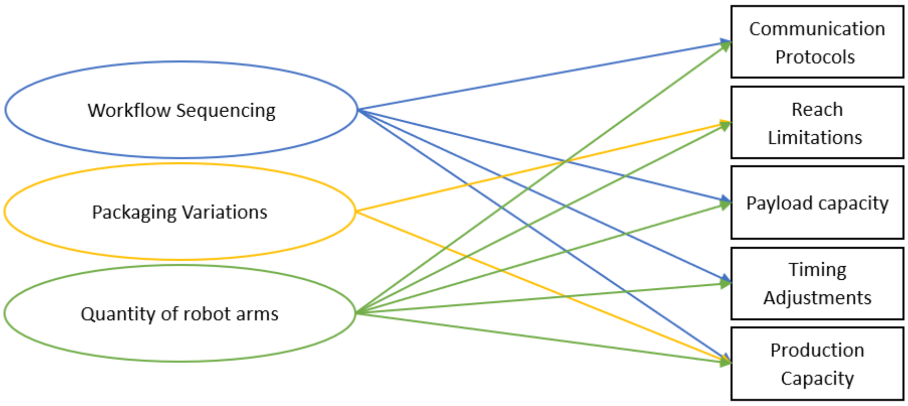


Figure 21- Correlation between parameters

3.2.1. Solution 1

- Quantity of arms: 1
- Quantity of grippers per arm: 4
- Quantity of cables moved per movement per arm: 4
- Visual inspections details: camera/checking station 1 and 2 outside the arm
- Prepackaging details: one prepackaging performed by Robocop

One potential solution involves utilizing a specially adapted robot arm equipped with a quadruple claw designed to grasp four cables simultaneously. The claw incorporates four micro grippers that can operate independently if required. The operation consists of five sequential sub-operations:

1. Cable Placement:

The Robocop positions the cables with Zamak terminals, which have been previously injected, into an intermediate packaging jig. This jig features pre-defined positions that correspond to the mold cavities. The Robocop places two cables at a time.

2. Inspection Area:

The robot arm with the quadruple gripper takes the four cables and transports them through an inspection area. This step ensures that any git residue has been effectively removed.

3. Over-Injection:

Once the cables have passed the inspection successfully, the arm places them into the equipment for the over-injection process, placement on the mold for plastic injection shown in Figure 22Figure 22- Cable end Fittings Positioned in Mold Before Plastic Injection

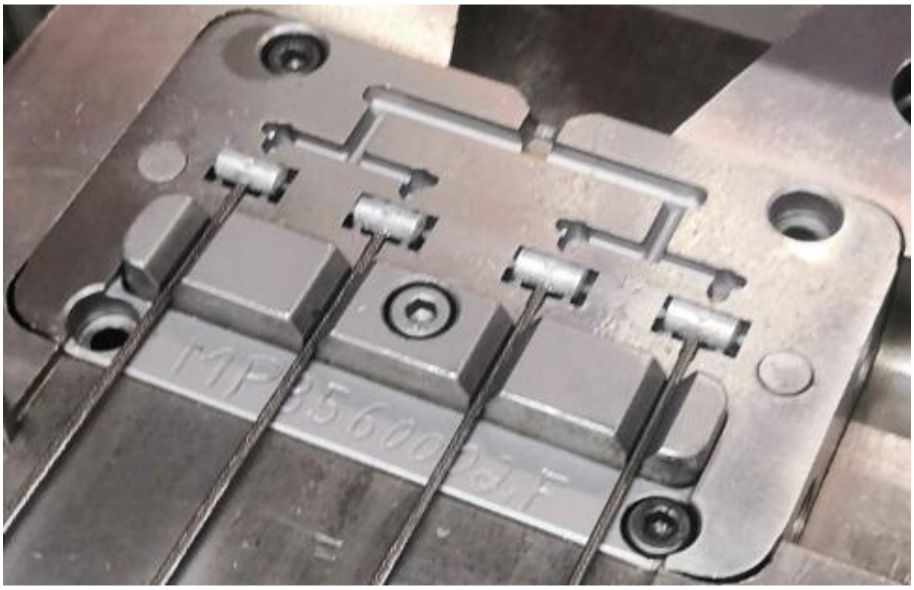


Figure 22- Cable end Fittings Positioned in Mold Before Plastic Injection

4. Post-Injection Inspection:

While the cables are being injected, the robotic arm retrieves the four cables that were previously over-injected (example of cables after plastic injection shown in Figure 23) and guides them through an inspection area. This inspection verifies that any remaining git has been completely removed.

Figure 23 - Cable end Fittings Positioned in Mold After Plastic Injection

5. Packaging:

After passing the inspection in step 4, the arm proceeds to pack the four injected cables, preparing them for further handling or shipment.

The process then returns to step 2, and the cycle continues, allowing for the continuous and repetitive execution of the operation.

By implementing this solution, the robotic arm with its adapted claw facilitates the efficient handling and processing of multiple cables simultaneously, ensuring the necessary inspections are conducted at each stage of the operation.

Advantages

1. Increased Cable Handling Efficiency: Using a robotic arm with an adapted claw capable of grabbing four cables simultaneously allows for efficient handling of multiple cables at once. This reduces the overall cycle time and increases the production output.

Disadvantages

1. Complex Claw Design: Developing a claw capable of simultaneously gripping four cables may require a more complex and specialized design. This could result in increased costs for manufacturing and maintenance compared to simpler claw designs.
2. Limited Flexibility: The solution's design specifically caters to handling four cables at once. If there is a need to handle a different number of cables or adapt to varying production requirements, the claw design may not be easily adjustable, potentially limiting its flexibility.
3. Higher Initial Investment: Implementing a robotic arm with a quadruple gripper involves higher initial investment costs compared to a single or double gripper system. This can impact the overall project budget and return on investment considerations.
4. Increased Maintenance Complexity: With the integration of multiple micro grippers, the maintenance and calibration of the robotic arm's claw system may become more intricate and time-consuming. This could result in higher maintenance costs and potential downtime if maintenance activities are not properly planned and executed.

A schematic representation of the solution is shown in Figure 24.

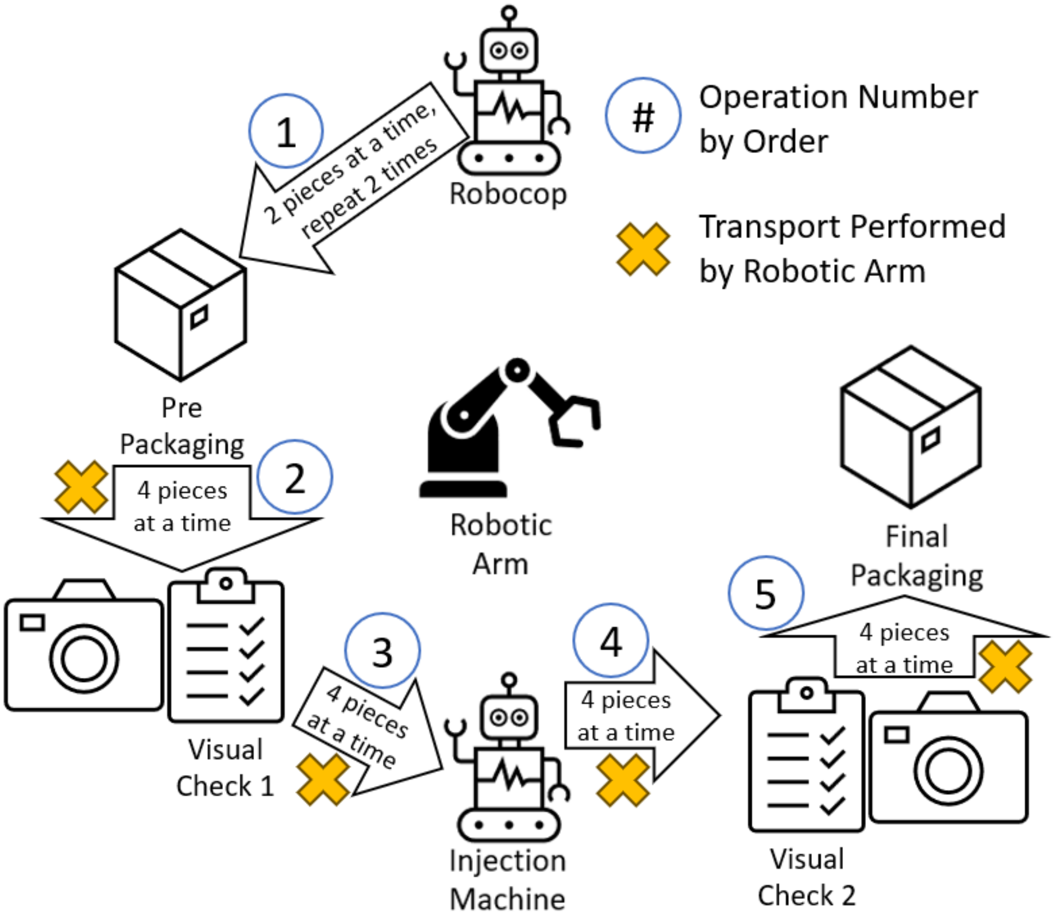


Figure 24 - Solution 1 Schematic Representation

3.2.2. Solution 2

- Quantity of arms: 2
- Quantity of grippers per arm: 2
- Quantity of cables moved per movement per arm: 2
- Visual inspections details: camera/checking station 1 and 2 outside the arm
- Prepackaging details: not applicable

The second solution involves the use of two robotic arms, each equipped with a specially adapted claw capable of securely holding two cables simultaneously. Each claw is equipped with two micro grippers that can operate independently as needed. The operation consists of four distinct sub-operations, with two associated with the first robotic arm (referred to as Arm 1) and two associated with the second robotic arm (referred to as Arm 2). These sub-operations are performed in parallel, optimizing efficiency.

1. Cable Inspection and Transfer (Arm 1):

Arm 1, utilizing its double gripper, directly retrieves the two cables from Robocop's manipulator. The arm then guides the cables through an inspection zone to ensure the removal of any unwanted particles or contaminants.

2. Mold Placement (Arm 1):

After the cables have successfully passed the inspection, Arm 1 proceeds to place the same cables into the empty mold (Figure 25), ready for the over-injection process.

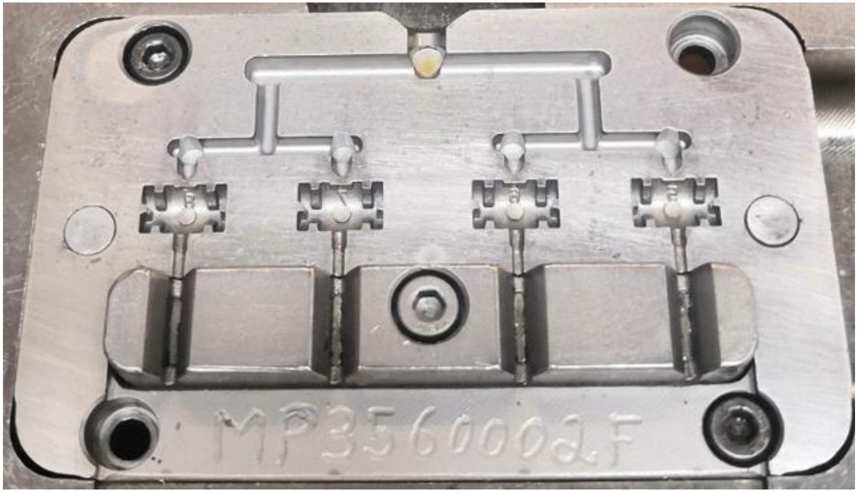


Figure 25 - Empty Mold

3. Post-Injection Inspection (Arm 2):

Arm 2, equipped with its double gripper, takes the two previously over-injected cables and guides them through an inspection area. This inspection ensures the complete removal of any residual particles or contaminants.

4. Packaging (Arm 2):

Upon successfully passing the inspection in step 3, Arm 2 proceeds to pack the two injected cables, preparing them for further handling or shipment.

By employing this solution, the two robotic arms, each with their adapted claws, work in tandem to facilitate the handling, inspection, and packaging of the cables. Arm 1 focuses on the initial cable transfer and mold placement, while Arm 2 handles the post-injection inspection and packaging tasks. This parallel workflow increases productivity and streamlines the overall operation.

Advantages

1. Parallel Processing: By using two robotic arms, each equipped with a double gripper, the solution allows for parallel processing of cable handling and inspection tasks. This leads to increased production efficiency and throughput.

Disadvantages

1. Increased Equipment and Space Requirements: Implementing two robotic arms with double grippers necessitates additional equipment and space compared to a single-arm solution. This can result in higher initial investment costs and require sufficient floor space for accommodating the additional equipment.

2. Coordination and Synchronization Challenges: Coordinating the movements and tasks of two robotic arms simultaneously can present challenges in terms of synchronization and programming. Ensuring smooth and efficient operation requires careful planning and programming of the robotic arm movements.

3. Higher Maintenance and Calibration Needs: With the integration of multiple robotic arms and grippers, the maintenance and calibration requirements may be more complex compared to a single-arm solution. This can result in increased maintenance costs and potential downtime for calibration and troubleshooting.

A schematic representation of the solution is shown in Figure 26.

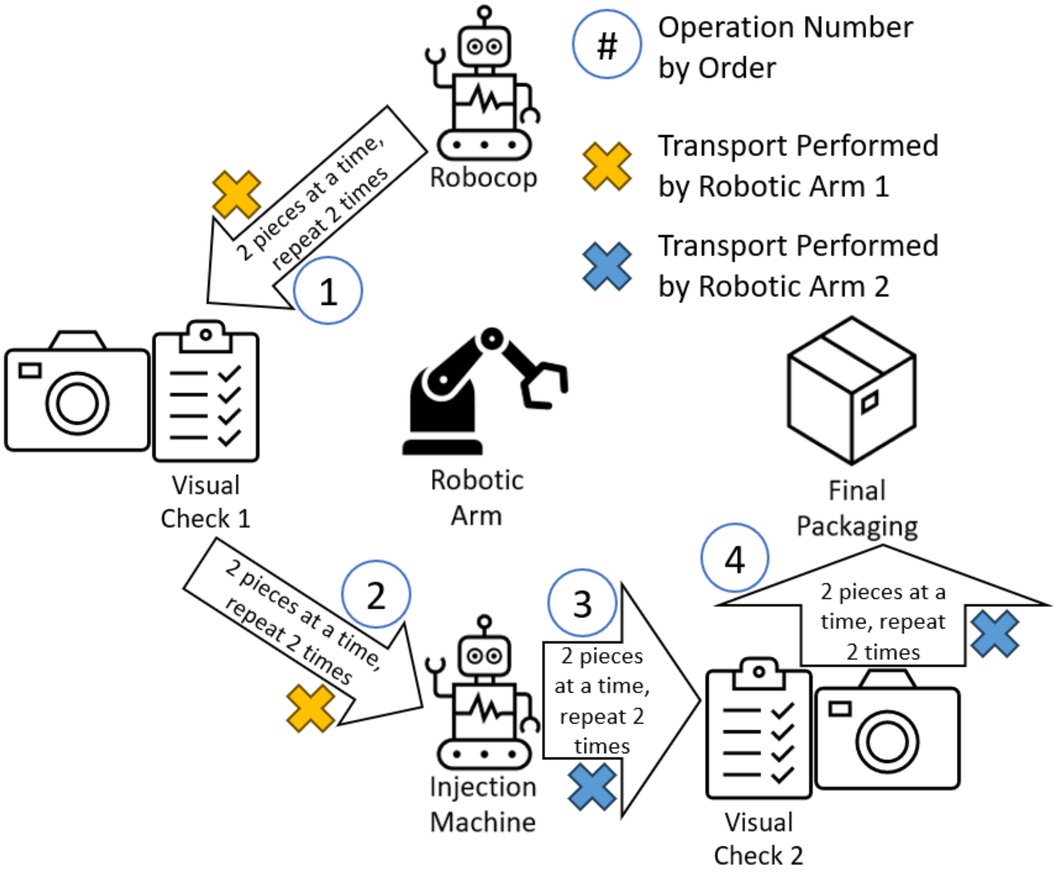


Figure 26 - Solution 2 Schematic Representation

3.2.3. Solution 3

- Quantity of arms: 2
- Quantity of grippers per arm: 1
- Quantity of cables moved per movement per arm: 2
- Visual inspections details: camera attached to the robotic, checking station 1 and 2 outside the arm
- Prepackaging details: not applicable

The third solution involves the utilization of two robotic arms, each equipped with an extended claw Figure 27 capable of securely holding two cables simultaneously. Additionally, a camera is integrated into each robotic arm, enabling real-time verification of git removal during cable transportation without the need for pauses or interruptions. The operation consists of two sub-operations, one associated with Robotic Arm 1 and the other associated with Robotic Arm 2, both performed in parallel for enhanced efficiency.

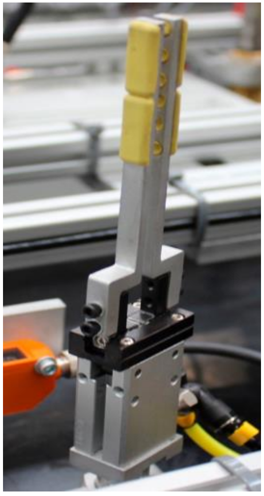


Figure 27 - Extended Claw

1. Cable Transportation and Mold Placement (Robotic Arm 1):

Robotic Arm 1 retrieves the two cables directly from the Robocop manipulator. During the transportation of the cables to the injection machine, the arm utilizes the integrated camera to conduct a git removal check. Upon successfully passing this inspection, the cables are promptly placed in the mold for further processing.

2. Cable Transportation and Packaging (Robotic Arm 2):

Robotic Arm 2 takes the two cables that have undergone over-injection. During the transportation of these cables to the packaging area, the arm conducts a gyto removal check using the camera system. If the inspection is successful, the arm proceeds to pack the cables, preparing them for subsequent handling or shipment.

By implementing this solution, the two robotic arms, each equipped with an extended claw and a dedicated camera system, work simultaneously to ensure smooth and efficient operations. Robotic Arm 1 focuses on cable transportation and mold placement while conducting the git removal check. Robotic Arm 2 handles the transportation of over-injected cables, performs the git removal check, and carries out the packaging process. This parallel approach optimizes productivity while ensuring the necessary quality checks are conducted throughout the operation.

Advantages

1. Enhanced Cable Handling Efficiency: Using two robotic arms, each equipped with a long claw and a camera for git removal verification, enables efficient cable handling and

inspection. The long claw allows for simultaneous gripping of two cables, increasing productivity, while the camera ensures git removal without the need for pauses, ensuring continuous workflow.

2. Parallel Processing with Independent Arms: The solution allows for parallel processing with independent robotic arms. This means that each arm can perform its tasks simultaneously, reducing cycle times and improving overall production efficiency.

3. Streamlined Packaging Process: With the robotic arms performing cable handling, transportation, and inspection, followed by packaging, the solution streamlines the entire process. This integration reduces manual intervention, eliminates the need for additional equipment or personnel, and enhances production flow.

Disadvantages

1. Complex System Integration: Implementing a solution with two robotic arms, cameras, and advanced inspection capabilities requires intricate system integration. This complexity may result in challenges related to programming, synchronization, and calibration, which may require specialized expertise and additional time and resources.

2. Higher Initial Investment and Maintenance Costs: The advanced features and equipment involved in Solution 3 can lead to higher initial investment costs compared to simpler solutions. Additionally, the system's complexity may result in increased maintenance and calibration requirements, potentially adding to the overall operational costs.

A schematic representation of the solution is shown in Figure 28.

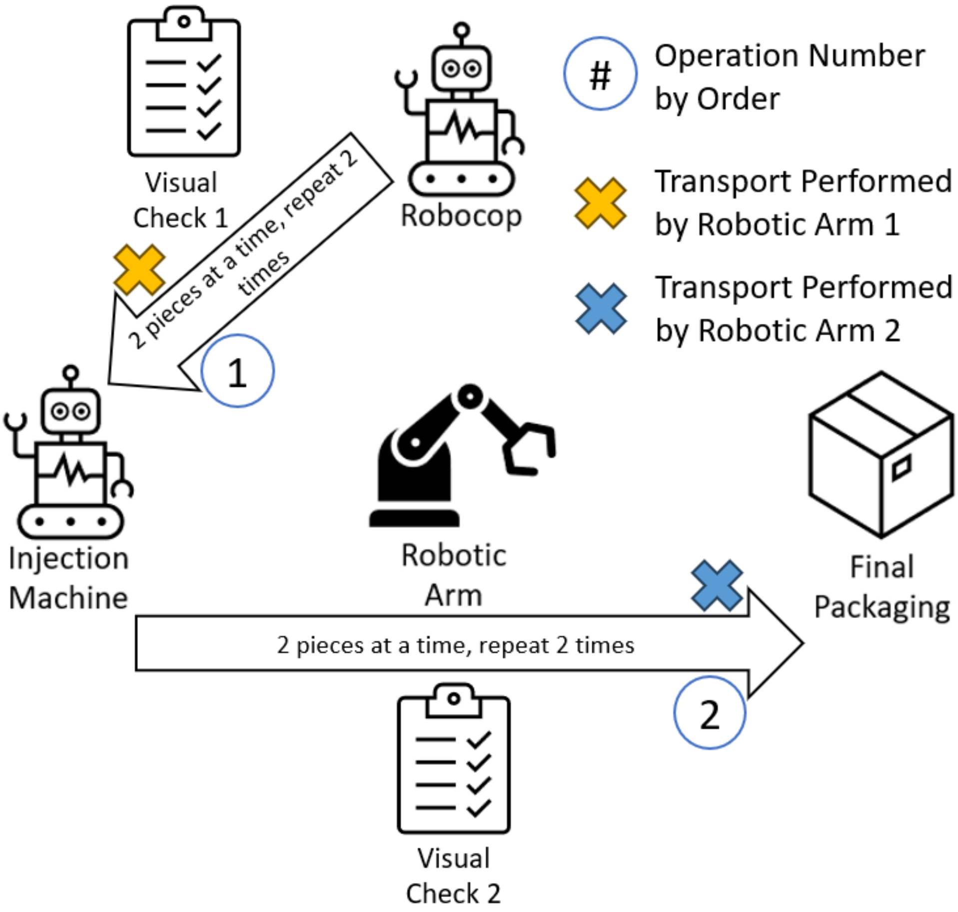


Figure 28 - Solution 3 Schematic Representation

3.2.4. Solution 4

- Quantity of arms: 1
- Quantity of grippers per arm: 1
- Quantity of cables moved per movement per arm: 2
- Visual inspections details: camera attached to the robotic, checking station 1 and 2 outside the arm
- Prepackaging details: one prepackaging performed by robocop

The fourth solution involves the utilization of a single robotic arm equipped with an extended claw capable of simultaneously grasping two cables. The arm is also equipped with a camera system that enables real-time verification of git removal during transportation, eliminating the need for pauses or interruptions. The operation consists of three sub-operations, with one associated with Robocop and two associated with the robotic arm, as follows:

1. Cable Placement by Robocop:

Robocop places the cables (Robocop Injecting and Moving two Cables is shown in Figure 29), which already have the Zamak terminal injected, into an intermediate packaging jig. The jig is designed with predefined positions that correspond to the mold cavities. Robocop places two cables at a time into the jig.

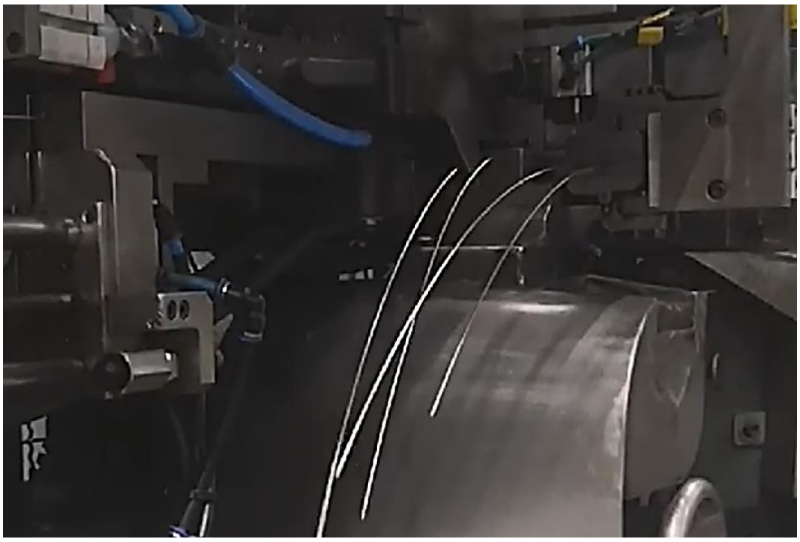


Figure 29 - Robocop Injecting and Moving two Cables per Move

2. Cable Transportation and Mold Injection (Robotic Arm):

The robotic arm picks up the two cables from the packaging jig and performs a visual inspection during their transportation to the mold. Upon successfully passing the inspection, the arm places the cables into their respective cavities for overinjection.

3. Cable Transportation and Packaging (Robotic Arm):

While the previously injected cables are being overinjected, the robotic arm retrieves two cables that have completed the injection process. It then performs an inspection to ensure the git has been successfully removed during transportation to the packaging area. If the verification is successful, the arm proceeds to pack the two injected cables.

The cycle then returns to Step 2, and the process repeats.

By implementing this solution, a single robotic arm with an extended claw and an integrated camera system is utilized to streamline the operation. Robocop is responsible for the initial cable placement in the packaging jig. The robotic arm handles cable transportation, visual inspections, mold injection, git removal checks, and packaging. This efficient and continuous workflow ensures consistent production while maintaining the necessary quality control measures throughout the process.

Advantages

1. Simplified Workflow: Solution 4 utilizes a single robotic arm equipped with a long claw and a camera, which simplifies the overall workflow. With a single arm performing multiple tasks, there is reduced complexity in system integration and coordination.
2. Real-time git Removal Verification: The integrated camera in the robotic arm enables real-time verification of git removal during cable transportation. This eliminates the need for pauses or additional inspection stations, leading to a continuous workflow and optimized production.

Disadvantages

1. Higher Dependency on a Single Arm: The reliance on a single robotic arm for multiple operations increases the risk of bottlenecks or slowdowns in the workflow. If the arm experiences any issues or requires maintenance, it can halt the entire process until the problem is resolved.

A schematic representation of the solution is shown in Figure 30.

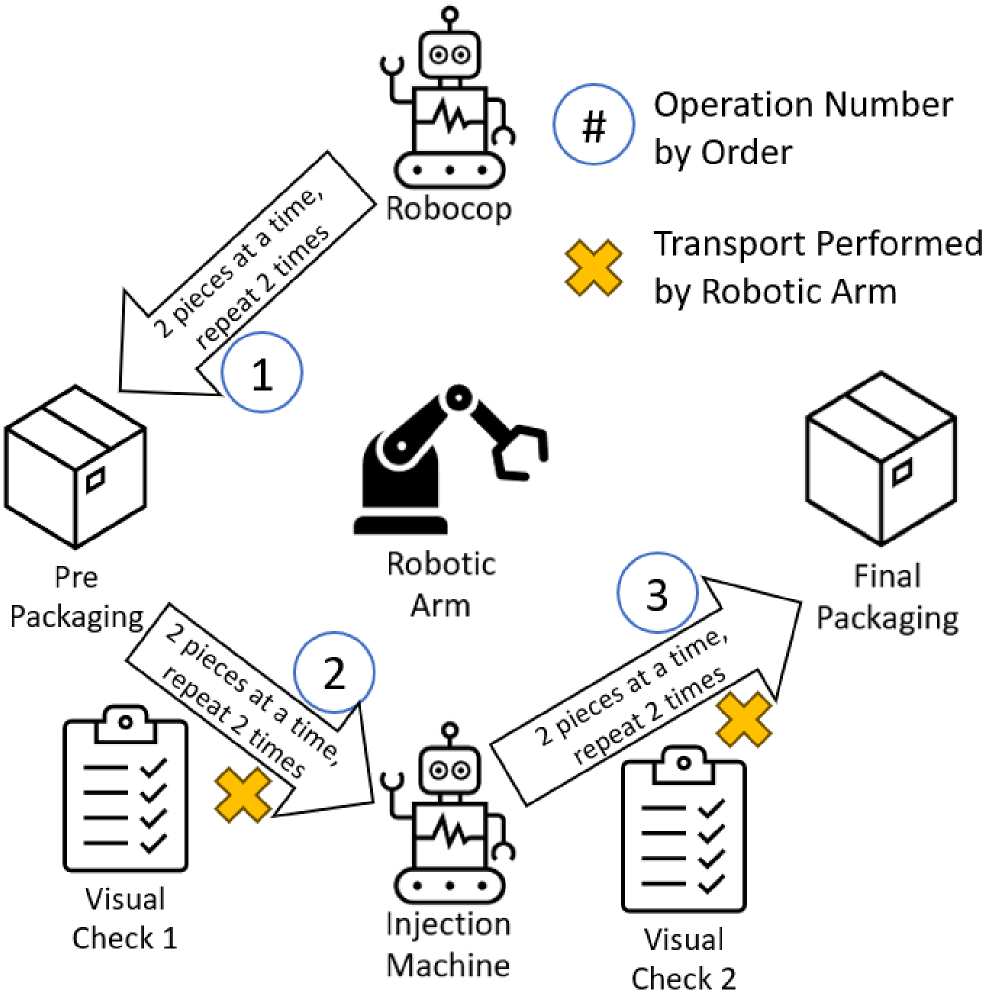


Figure 30 - Solution 4 Schematic Representation

3.3. Consulting Partner

As a current partner of Ficocables, Fluidotronica is a leading company at the forefront of automation solutions, revolutionizing industries with cutting-edge technology and unparalleled expertise. With a rich history spanning several decades, Fluidotronica has established itself as a trusted partner, delivering innovative and customized automation solutions to clients worldwide. Their team of skilled engineers, designers, and technicians work collaboratively to develop state-of-the-art automation systems that streamline processes, enhance productivity, and improve overall operational efficiency for their clients [13].

Headquartered in Portugal, Fluidotronica has a global presence, catering to diverse industries such as automotive, electronics, aerospace, and more. Their comprehensive range of automation solutions includes robotic arms, intelligent control systems, precision vision systems, and specialized equipment designed to meet the unique requirements of each industry.

What sets Fluidotronica apart is their dedication to delivering tailored solutions that address specific challenges faced by their clients. They understand that every business is unique, and they strive to develop customized automation systems that align with their clients' goals and objectives. Through close collaboration, they ensure that their solutions not only meet but exceed expectations, empowering businesses to stay competitive in today's rapidly evolving market.

With a strong focus on research and development, Fluidotronica consistently pushes the boundaries of automation technology. They stay ahead of industry trends, integrating the latest advancements in robotics, artificial intelligence, machine learning, and data analytics into our solutions. This enables their clients to leverage state-of-the-art technology, optimize their operations, and unlock new levels of efficiency and productivity.

Their team works closely with clients throughout the entire project lifecycle, ensuring seamless integration of our automation systems into their existing infrastructure and providing comprehensive training and maintenance services.

3.3.1. Interest for the project

In the realm of robotic arm projects, harnessing the knowledge and expertise of a trusted partner is paramount. Fluidotronica, with its extensive experience and specialized services, emerges as a valuable asset in enhancing the effectiveness and efficiency of this project.

Fluidotronica invests time in understanding our project requirements, challenges, and goals. Their team engages in thorough consultations to gain a comprehensive understanding of our specific needs. This consultative approach ensures that the solutions they provide align perfectly with the project objectives.

Drawing upon their vast experience and industry knowledge, Fluidotronica excels at identifying potential challenges and risks in advance. Their team proactively addresses these issues, offering innovative solutions to overcome obstacles and ensuring a smooth progression of this robotic arm project.

Fluidotronica's commitment to this project extends beyond its implementation. They provide ongoing support and maintenance services to ensure the optimal performance and longevity of your robotic arm system. Their dedicated team is readily available to address any inquiries or concerns you may have, ensuring our project's success even after its completion.

By collaborating with Fluidotronica, we gain access to their expertise, cutting-edge technology, comprehensive support, industry experience, and a collaborative partnership. This synergistic relationship empowers this robotic arm project, enabling us to achieve our goals efficiently and effectively.

3.3.2. Exploring Robotic Arm Possibilities with Fluidotronica

I was first introduced to Fluidotronica through my co-worker, Engineer Mário Soares, who works in the process department. Given their expertise in standalone solutions and their existing partnership with our company, it was highly advantageous and convenient to engage with Fluidotronica for technical support and potential further development of our current project solution. Their established presence as one of our suppliers made them a reliable and valuable resource to tap into.

Following several interactions with Fluidotronica's customer support, I was eventually connected with Engineer Rui Grilo, the Director of the HANDLING Fluidotronica Business Area. Throughout our collaboration, he served as the main point of contact and provided invaluable support. The process commenced by presenting the problem at hand, initially through phone conversations and the exchange of videos and photos showcasing the relevant equipment. In the final phase, potential solutions that had already been considered were shared, accompanied by PowerPoint presentations to provide further clarity and explanation.

During the subsequent phase of our collaboration, Engineer Rui Grilo suggested a visit to the Fluidotronica facilities. This visit offered an opportunity for me to present the actual input and output products of the process in question, namely the cable with the injected Zamak terminal and the cable with the plastic terminal over-injected in the Zamak terminal. Additionally, I brought along a sample mold that is utilized in this particular process. This hands-on presentation allowed for a more comprehensive understanding of the project requirements and facilitated a closer examination of the potential solutions offered by Fluidotronica.

The visit commenced with an informative presentation by Engineer Rui Grilo, providing a comprehensive overview of Fluidotronica's state-of-the-art facilities. Subsequently, we convened in a dedicated meeting room to engage in a detailed discussion regarding the optimal solution for our project. Drawing upon the extensive information and considerations shared earlier, we carefully evaluated each solution's risks, advantages, and disadvantages.

After thorough deliberation, a consensus was achieved putting solutions 3 and 4 as the most suitable options for our specific task. These solutions stood out due to their compelling attributes, encompassing factors such as efficiency, flexibility, simplicity, and cost. Acknowledging the complexity of the project and the importance of making an informed decision, we concurred that further analysis and evaluation of solutions 3 and 4 would be necessary. These solutions demonstrated significant potential in addressing our objectives and mitigating associated risks effectively. Therefore, subsequent chapters will delve deeper into the detailed examination and evaluation of these solutions, considering various technical aspects, feasibility, and cost-effectiveness.

3.3.3. Arm Selection

To proceed with the detailed analysis of solution 3 and 4 it was necessary to select an existing robot arm from the Fluidotronica catalogue. The company works mainly with the Jaka.

JAKA is an innovative robotics company specializing in industrial automation. With a focus on collaborative robotics, their solutions, such as the JAKA Zu 3s Collaborative Robot, enable safe and efficient human-robot interaction. Known for their commitment to quality and customer satisfaction, JAKA offers advanced robotic systems designed to enhance productivity and streamline processes across various industries. Through continuous research and development, JAKA remains at the forefront of technological innovation in automation, delivering user-friendly solutions backed by comprehensive technical support and training services.

For the project being developed the JAKA Zu 3s Collaborative Robot was selected due to several compelling reasons.

First and foremost, the collaborative nature of the robot makes it ideal for working alongside human operators in a shared workspace. It is designed to prioritize safety, incorporating advanced sensors and safety features to detect and respond to human presence, reducing the risk of accidents or injuries.

Additionally, the JAKA Zu 3s offers impressive versatility and flexibility. Its modular design allows for easy customization and integration into existing workflows. With a payload capacity of 3 kg and a reach of 626 mm, it can handle a wide range of tasks, including picking and placing objects, assembly, and material handling.

The robot is equipped with advanced motion control and precision positioning, ensuring accurate and repeatable performance. This level of precision is crucial for the specific requirements of the project, where precise movements and positioning are essential for successful operations.
A more detailed description of the arm will be provided on next point.

3.3.4. JAKA Zu 3s Collaborative Robot

The JAKA Zu 3s Collaborative Robot is an advanced robotic solution designed for collaborative work environments. With its cutting-edge features and user-friendly design, it offers a range of benefits for various industrial applications.
The JAKA Zu 3s Collaborative Robot shown in Figure 31 belongs to the renowned ''zu'' line of robotics offered by Jaka Robotics. As part of this line, the ''3'' model signifies its suitability for lower load applications. The addition of the ''s'' indicates that it belongs to the range equipped with force sensors on all six axes of the robot's arm.

Figure 31 - JAKA Zu 3s Collaborative Robot [14]

The robot is specifically engineered to operate safely alongside human workers, promoting a harmonious interaction between man and machine. Equipped with advanced sensors and safety systems, it can detect and respond to human presence, ensuring a high level of safety in shared workspaces.

Versatility is a key aspect of the JAKA Zu 3s. Its modular design allows for easy customization and integration into existing workflows. With a payload capacity of 3 kg and a reach of 626 millimeters, it is capable of handling a wide range of tasks, including material handling, assembly, and picking and placing objects with precision and accuracy.

The JAKA Zu 3s Collaborative Robot incorporates advanced motion control technology, enabling smooth and precise movements. It offers exceptional repeatability and positioning accuracy, ensuring consistent performance in various industrial operations.

A list of the most relevant parameters taken from the Jaka Robotics official web site is shown in the Table 1 and Table 2 below:

Table 1 - Arm Specifications [14]

Technical Feature	
Payload	3 kg
Weight (W cable)	12 kg
Working Radius	626 mm
Repeatability	±0.02mm
Axis	6
Programming	Graphical/Visual
Teach Pendant	MT(PAD/Mobile)APP
Collaborative operation	In compliance with GB 11291.1-2011
Certifications	CR, CE, 15066
Temperature Range	0-50℃
Installation	At any angle

Table 2 - Arm Kinematic Specifications [14]

Robot	**Workscope**	**Max Speed**
Joint 1	±360°	180°/s
Joint 2	-85°， +265°	180°/s
Joint 3	±175°	180°/s
Joint 4	-85°， +265°	220°/s
Joint 5	±360°	220°/s
Joint 6	±360°	220°/s
Max Speed	-	1.5 m/s

3.4. Capacity Calculation

Based on the selected robotic arm and the specifications provided, we can now estimate the production capacity of solutions 3 and 4. To facilitate this analysis, we will consider layouts that minimize arms movements. It is worth noting that the previously introduced Robocop show in Figure 32 has a production capacity of 800 pieces per hour, with a throughput of 2 pieces per cycle. With this information, we can assume that the Robocop completes one full cycle every 9 seconds.
It is important to note that the production capacity can be enhanced over the course of the project. However, achieving this requires a comprehensive analysis of the various layouts of the integrated equipment and the optimization of arm movements. Such an analysis is a substantial task in itself. Therefore, for the purpose of this project, we will proceed with an approximate calculation to establish a baseline production capacity.

Figure 32 - Robocop Machine

3.4.1. Solution 3

During the analysis of solution 3, it became apparent that it would not be an efficient option for the project. The injection machine used in the process operates with two molds, where one mold is being injected while the other is outside, ready to be emptied and reloaded. Implementing two robotic arms simultaneously in this scenario would result in significant downtime for both arms. One arm would be engaged in loading the mold, while the other arm would be responsible for packaging the final product.

Considering the specifications of the selected arm and the operational requirements, it was concluded that focusing on solution 4 would be a more suitable approach. Solution 4, which involves using a single robotic arm, offers a better utilization of resources and minimizes downtime. The arm can perform the necessary tasks of loading the mold, performing inspections, and packaging the injected cables sequentially without the need for coordination with another arm. This streamlines the production process and ensures a more efficient operation.

Taking these factors into account, it was determined that solution 4 aligns better with the project's objectives and provides a more effective and optimized workflow. Therefore, the project will proceed with a detailed analysis and implementation plan for solution 4.

3.4.2. Solution 4

The implementation of solution 4 aims to minimize the downtime of the Robotic Arm, maximizing its capacity utilization. To calculate the production capacity, the focus was initially on the arm's angular movements, excluding the time required for gripping or positioning components.

By analyzing the angular movements, it was possible to determine the minimum time required for the arm to complete its operation. In practical application, additional factors such as the gripping and positioning time of components, as well as any potential variations or delays in the process, need to be considered for a more accurate assessment.

The layout of this solution is presented on Figure 33, we will consider 60° between each blue line.

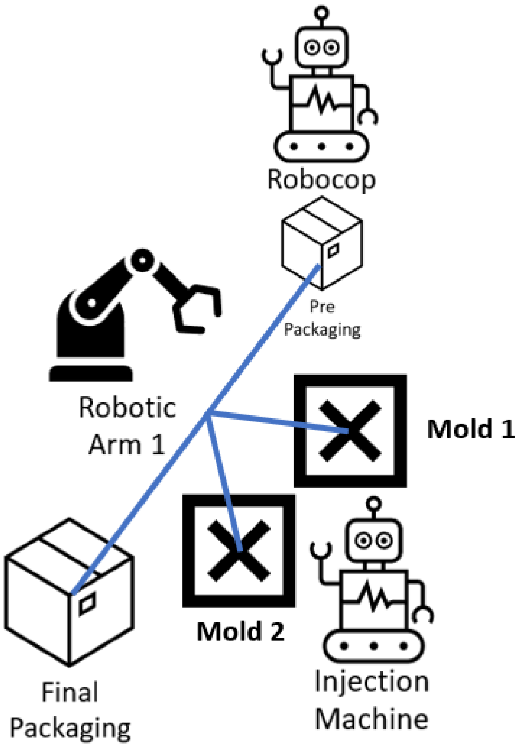


Figure 33 - Solution 4 Layout

To initiate this analysis, an Excel table was developed outlining the specific steps that the Robotic Arm needs to execute in order to complete a cycle. It is important to note that the first twelve moves of the arm serve as the starting point of production. For analysis, the focus will be the 1st cycle, which encompasses steps 13 to 28. It is at this point that the repetitive pattern begins. Additionally, we must consider Mold 1 and Mold 2 separately, as their relative positions in relation to other components differ.

Upon reviewing the Table 3 it’s possible to conclude that a complete cycle involving the placement, injection, and extraction of both Mold 1 and Mold 2 requires approximately 8.67 seconds of macro movements for the Robotic Arm. Within this cycle, a total of 8 cables are produced. As for the Robocop machine, it will need approximately 36 seconds to generate the necessary material for the operation.

Table 3 - Macro Movements Time Calculation

Move #	Movement Step	Cicle	Movement Angle (°)	Time Spent Per Movement (s)	Total Time Spent (s)	Production	Robocop Time
1	Pre Packaging->Injection Machine Mold 1	Process Start-Up	-	-	-	-	-
2	Injection Machine Mold 1->Pre Packaging		-	-	-	-	-
3	Pre Packaging->Injection Machine Mold 1		-	-	-	-	-
4	Injection Machine Mold 1->Pre Packaging		-	-	-	-	-
5	Pre Packaging->Injection Machine Mold 2		-	-	-	-	-
6	Injection Machine Mold 2->Pre Packaging		-	-	-	-	-
7	Pre Packaging->Injection Machine Mold 2		-	-	-	-	-
8	Injection Machine Mold 2->Injection Machine Mold 1		-	-	-	-	-
9	Injection Machine Mold 1->Final Packaging		-	-	-	-	-
10	Final Packaging->Injection Machine Mold 1		-	-	-	-	-
11	Injection Machine Mold 1->Final Packaging		-	-	-	-	-
12	Final Packaging->Pre Packaging		-	-	-	-	-
13	Pre Packaging->Injection Machine Mold 1	1	60	0.33	8.67	8 Final Product Produced	36
14	Injection Machine Mold 1->Pre Packaging		60	0.33			
15	Pre Packaging->Injection Machine Mold 1		60	0.33			
16	Injection Machine Mold 1->Injection Machine Mold 2		60	0.33			
17	Injection Machine Mold 2->Final Packaging		60	0.33			
18	Final Packaging->Injection Machine Mold 2		60	0.33			
19	Injection Machine Mold 2->Final Packaging		60	0.33			
20	Final Packaging->Pre Packaging		180	1.00			
21	Pre Packaging->Injection Machine Mold 2		120	0.67			
22	Injection Machine Mold 2->Pre Packaging		120	0.67			
23	Pre Packaging->Injection Machine Mold 2		120	0.67			
24	Injection Machine Mold 2->Injection Machine Mold 1		60	0.33			
25	Injection Machine Mold 1->Final Packaging		120	0.67			
26	Final Packaging->Injection Machine Mold 1		120	0.67			
27	Injection Machine Mold 1->Final Packaging		120	0.67			
28	Final Packaging->Pre Packaging		180	1.00			
29	Pre Packaging->Injection Machine Mold 1	2	60	0.33	8.67	8 Final Product Produced	36
30	Injection Machine Mold 1->Pre Packaging		60	0.33			
31	Pre Packaging->Injection Machine Mold 1		60	0.33			
32	Injection Machine Mold 1->Injection Machine Mold 2		60	0.33			
33	Injection Machine Mold 2->Final Packaging		60	0.33			
34	Final Packaging->Injection Machine Mold 2		60	0.33			
35	Injection Machine Mold 2->Final Packaging		60	0.33			
36	Final Packaging->Pre Packaging		180	1.00			
37	Pre Packaging->Injection Machine Mold 2		120	0.67			
38	Injection Machine Mold 2->Pre Packaging		120	0.67			
39	Pre Packaging->Injection Machine Mold 2		120	0.67			
40	Injection Machine Mold 2->Injection Machine Mold 1		60	0.33			
41	Injection Machine Mold 1->Final Packaging		120	0.67			
42	Final Packaging->Injection Machine Mold 1		120	0.67			
43	Injection Machine Mold 1->Final Packaging		120	0.67			
44	Final Packaging->Pre Packaging		180	1.00			

This analysis provides valuable insights into the time requirements for each step of the cycle and highlights the efficiency of the Robotic Arm in terms of macro movements. With the macro movements defined we can now define the times for the following specific operations:

- Picking 2 cables from Pre Packaging Gauge: 1,2 seconds
- Placing 2 cables on the Mold: 2 seconds
- Picking 2 cables from the Mold: 0,6 seconds
- Placing 2 cables on the Final Packaging: 0,4 seconds

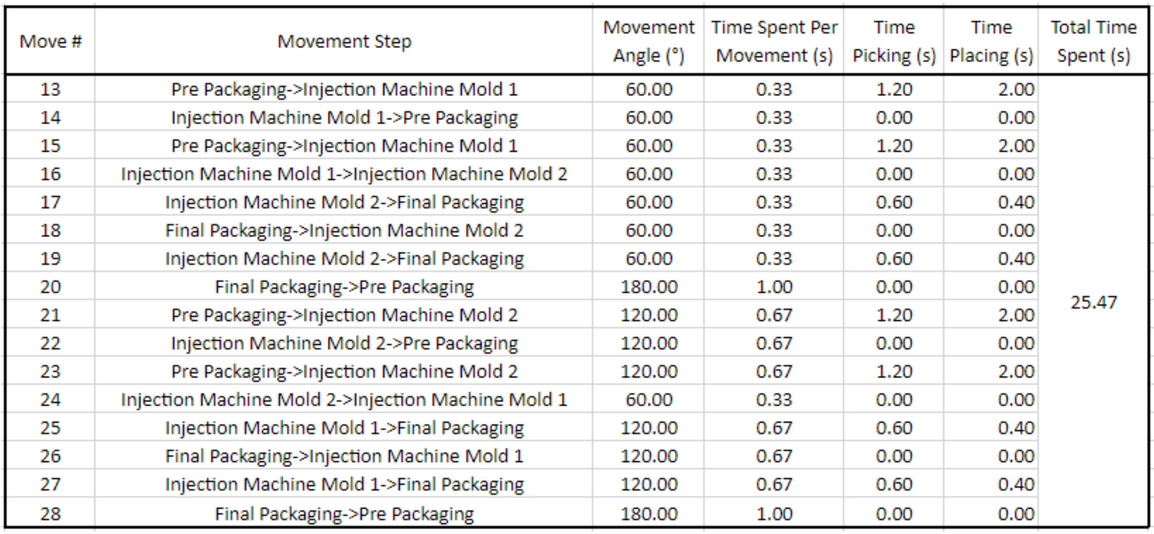
The time for both visual checks will not be considered in this project since this operation will be done during transportation, it will not represent significant increases in cycle time.

The time allocations were established considering the complexity and precision demands of each operation and are shown in Table 4. This accounts for the notable disparity in times between gripping the cables during pre-packaging and placing them in the mold, compared to gripping the cables from the mold and transferring them to the packaging area, where precision requirements are comparatively lower.

Having determined the time durations for each operation, the next step is to incorporate them into the existing table to calculate the total time for a complete cycle. As a result, the cumulative time amounts to 25.5 seconds.

By including these specific time measurements in our analysis, we gain a more comprehensive understanding of the overall duration of a cycle.

Table 4 - Cycle Time Calculation with Micro Movements



Move #	Movement Step	Movement Angle (°)	Time Spent Per Movement (s)	Time Picking (s)	Time Placing (s)	Total Time Spent (s)
13	Pre Packaging->Injection Machine Mold 1	60.00	0.33	1.20	2.00	25.47
14	Injection Machine Mold 1->Pre Packaging	60.00	0.33	0.00	0.00	
15	Pre Packaging->Injection Machine Mold 1	60.00	0.33	1.20	2.00	
16	Injection Machine Mold 1->Injection Machine Mold 2	60.00	0.33	0.00	0.00	
17	Injection Machine Mold 2->Final Packaging	60.00	0.33	0.60	0.40	
18	Final Packaging->Injection Machine Mold 2	60.00	0.33	0.00	0.00	
19	Injection Machine Mold 2->Final Packaging	60.00	0.33	0.60	0.40	
20	Final Packaging->Pre Packaging	180.00	1.00	0.00	0.00	
21	Pre Packaging->Injection Machine Mold 2	120.00	0.67	1.20	2.00	
22	Injection Machine Mold 2->Pre Packaging	120.00	0.67	0.00	0.00	
23	Pre Packaging->Injection Machine Mold 2	120.00	0.67	1.20	2.00	
24	Injection Machine Mold 2->Injection Machine Mold 1	60.00	0.33	0.00	0.00	
25	Injection Machine Mold 1->Final Packaging	120.00	0.67	0.60	0.40	
26	Final Packaging->Injection Machine Mold 1	120.00	0.67	0.00	0.00	
27	Injection Machine Mold 1->Final Packaging	120.00	0.67	0.60	0.40	
28	Final Packaging->Pre Packaging	180.00	1.00	0.00	0.00	

After carefully evaluating the time requirements for the robotic arm and the supply of materials by the Robocop machine, we can confidently conclude that the implementation of solution 4 will not have any adverse impact on the previously defined production capacities.

With this information, we can assert that solution 4 is not only feasible but also capable of meeting the initially defined requirements. The integration of the robotic arm in the workflow ensures efficient operation while maintaining the desired production capacities. This solution provides a practical and effective approach to optimize the process, minimize downtime, and ensure smooth production flow.

By selecting solution 4, the project can proceed with confidence, knowing that it aligns with the established goals and objectives. The seamless integration of the robotic arm will enhance productivity and contribute to the overall success of the project.

3.5. Maintenance Protocols

In order to ensure the optimal performance and longevity of our robotic arm, it is crucial to implement effective maintenance protocols. For this purpose, we will diligently adhere to the maintenance manual provided by Jaka Robotics, the manufacturer of the arm.
This chapter focuses on the maintenance guidelines specific to the Jaka Robotics robotic arm, as outlined in their comprehensive manual. By following these protocols, we can

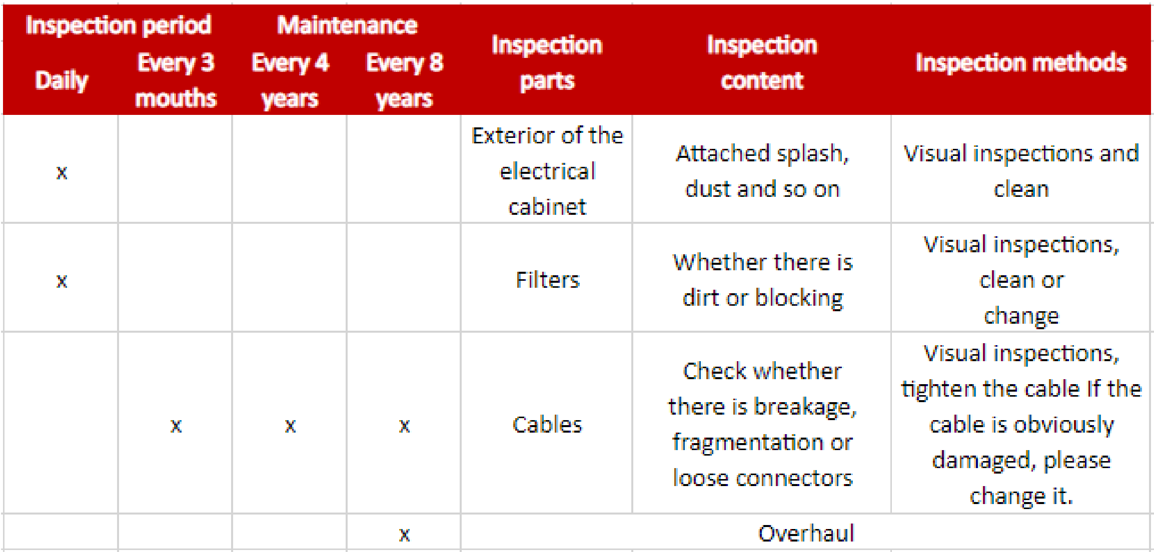
proactively address potential issues, minimize downtime, and maximize the arm's performance and lifespan.

Throughout this chapter, we will explore preventive measures, routine inspections, and troubleshooting procedures recommended by Jaka Robotics. Adhering to these protocols offers benefits such as improved efficiency, reduced costs, and enhanced safety.

In the Jaka Robotics maintenance manual the maintenance of the electric cabin and the robot are presented separately.

In accordance with the manual order, first the recommended preventive maintenance and inspection periods for the Electric Cabin are outlined in Table 5, providing guidance for ensuring the optimal condition and performance of this critical component.

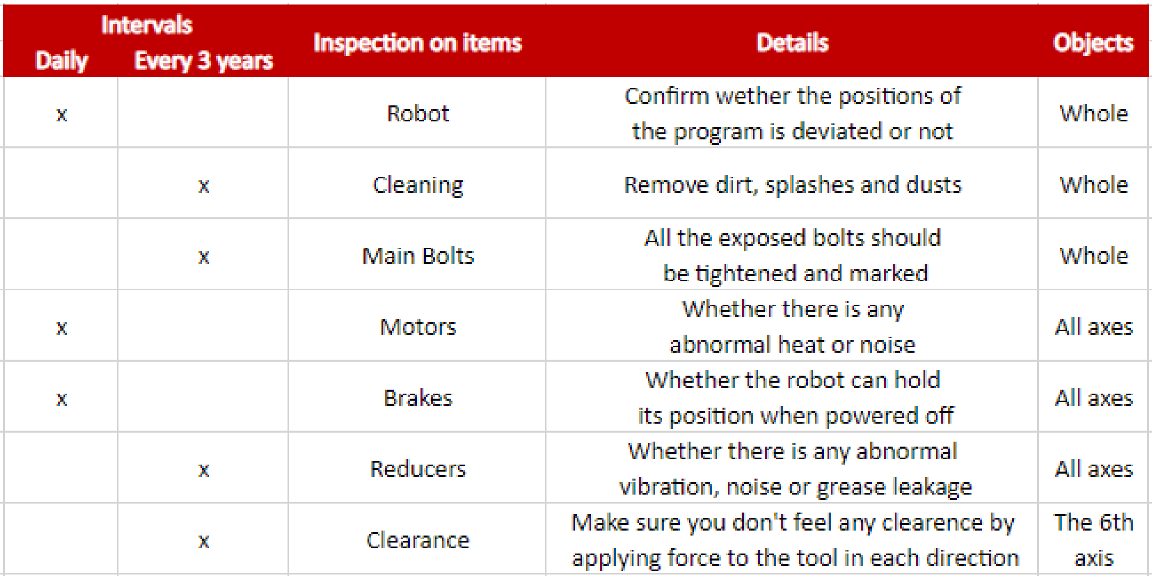
Table 5 - Electric Cabin Maintenence Protocols [14]



Inspection period		Maintenance		Inspection parts	Inspection content	Inspection methods
Daily	Every 3 mouths	Every 4 years	Every 8 years			
x				Exterior of the electrical cabinet	Attached splash, dust and so on	Visual inspections and clean
x				Filters	Whether there is dirt or blocking	Visual inspections, clean or change
	x	x	x	Cables	Check whether there is breakage, fragmentation or loose connectors	Visual inspections, tighten the cable If the cable is obviously damaged, please change it.
			x	Overhaul		

Now shifting focus to the maintenance protocols for the robotic arm, they are presented in Table 6. These protocols serve as a comprehensive reference for ensuring the proper upkeep and functionality of the arm throughout its operational lifespan.

Table 6 - Robotic Arm Maintenence Protocols [14]



Intervals		Inspection on items	Details	Objects
Daily	Every 3 years			
x		Robot	Confirm wether the positions of the program is deviated or not	Whole
	x	Cleaning	Remove dirt, splashes and dusts	Whole
	x	Main Bolts	All the exposed bolts should be tightened and marked	Whole
x		Motors	Whether there is any abnormal heat or noise	All axes
x		Brakes	Whether the robot can hold its position when powered off	All axes
	x	Reducers	Whether there is any abnormal vibration, noise or grease leakage	All axes
	x	Clearance	Make sure you don't feel any clearence by applying force to the tool in each direction	The 6th axis

The personnel entrusted with the maintenance responsibilities are required to diligently prepare and implement the designated maintenance plans. Their expertise and attentiveness in carrying out these plans are crucial to ensuring the optimal performance and longevity of the robotic arm.

4. RESULTS AND DISCUSSION

Financial analysis plays a crucial role in evaluating the feasibility and profitability of any project or investment. In this chapter, will be performed an analysis to the financial aspects of the project, aiming to assess its economic viability and potential returns. By conducting a comprehensive financial analysis it’s possible to identify risks and determine the project's potential impact on the organization's financial performance.

This chapter will explore various financial metrics, tools, and methods that will enable us to evaluate the investment's profitability, cash flow dynamics, and overall financial health. We will delve into key concepts such as net present value and Payback Period Analysis. For all the mentioned concepts a timeframe of 10 years was defined.

4.1. Net Present Value

To perform a Net Present Value analysis, the following inputs are necessary [15, p.368–369]:

1. Initial Investment Cost: This includes the cost of acquiring the robotic arm, installation costs, training expenses, software integration, and any other upfront costs related to implementing the automation process.
2. Cash Flows: Identify the cash inflows and outflows associated with the automation project over a specific time period. Cash inflows can include savings from labor costs, increased production efficiency, reduced errors, or any other financial benefits. Cash outflows include operating costs, maintenance expenses, and any other costs directly related to the operation of the robotic arm system.
3. Discount Rate: The discount rate represents the minimum desired rate of return or the cost of capital for the project. It takes into account the time value of money and the risk associated with the investment. The discount rate is typically based on the company's cost of capital or the required rate of return.

$$NPV = \sum(CFt \div (1+r)^{t}) + Initial\ Investment \tag{1}$$

Using these inputs, it’s possible to calculate the NPV by discounting the cash flows back to the present value using the discount rate. The formula for NPV is as follows:
Where CFt represents the cash flow in each period, r is the discount rate, t is the time period, and the summation (∑) is taken over the relevant time period.
A positive NPV indicates that the investment is expected to generate a positive return, while a negative NPV suggests that the investment may not be financially viable.
It's important to note that NPV analysis should consider the time value of money and provide a comprehensive evaluation of the financial viability of the robotic arm investment.

4.1.1. NPV Calculation

To perform the NPV calculation we must define the above-mentioned variables, following the previous sequence we will start with the Initial Investment.

By collaborating with Fluidotronica, an expert in autonomous solutions, the variable for the initial investment was determined by the budget provided by Fluidotronica, it was established that the cost for the project, including installation, would be approximately 16000 €. The arm's programming will be conducted utilizing internal resources, resulting in a minimal increase in the initial investment. However, to ensure a cautious approach, a decision to allocate an additional 10% to the initial budget was taken. This additional amount will cover the programming expenses as well as any unforeseen events that may arise during the project, providing a buffer for potential challenges or adjustments that may be required. With this we have an Initial Investment of 17600 €.

Turning now to the definition/calculation of cashflows the following inputs were considered:

- Cash Outflows:
    - Operation costs
    - Maintenance/Inspection Expenses
- Cash Inflows
    - Labor Savings

Starting with the operating costs of the arm and comparing them with the hourly price of an operator are by no means comparable. In order to calculate two different working scenarios, on an initial stage will be considered the hourly price of the arm. Depending on the power supplier for the company the prices can range from 0,08 €/kWh to 0,16 €/kWh, for this reason will be used an average price of 0,12 €/kWh, it is important to state that this figure is quite conservative and that in a real business scenario the hourly rates are much lower.

Switching to maintenance costs, these will be calculated on the basis of the protocols defined by the arm manufacturer, discussed above. For the maintenance of the electric cabin, it was considered an inspection, and if necessary, change of electric wiring every 4 years, based on this we defined 200 € as an approximate value for this operation. The other maintenance is performed every 8 years and is general, any component that may be damaged may need replacement, so 1000 € will be considered for this intervention.

Also, for the electric cabin, the arm manufacturer advises a daily inspection of the filters and the cabin exterior, assuming a duration of 5 minutes for this task this would result in 1800 minutes per year spent on this inspection, or 45 hours of work.

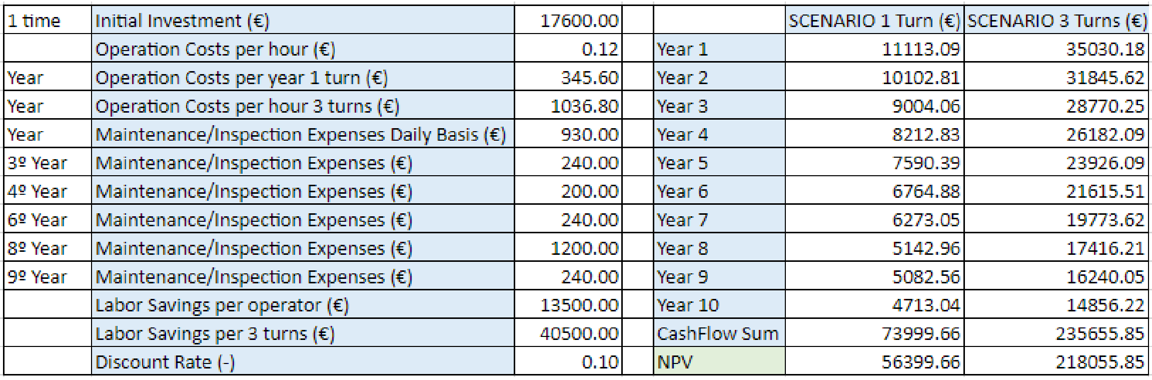
Moving on now to the maintenance of the arm, more specifically, 3 daily inspections have been defined, we will consider a time of 8 min for them, resulting on 48 h of work, this time is based on similar equipment already existing in the company. Finally, it is necessary to consider 4 inspections that should be carried out every 3 years. These include a complete cleaning of the equipment, a check of the tightness of the screws, a check for vibrations or abnormal noises, and finally a functional check of the fluidity of the sixth axis, for this task we will define 4 hours and an expense of 200 € on spare parts. For all the technical operations we will consider 10 €/hour pay.

For last the labor saving per operator are approximately 13500 € per year, considering the minimum wage.

The only variable left to define is the discount rate, that after discussion was defined as 10%.

Entering this data into an Excel sheet presented in Table 7 an NPV of 56400 € for a 1-shift work schedule and an NPV of 218000 € for a 3-shift work schedule were obtained.

Table 7 - NPV Calculation



1 time	Initial Investment (€)	17600.00			SCENARIO 1 Turn (€)	SCENARIO 3 Turns (€)
	Operation Costs per hour (€)	0.12		Year 1	11113.09	35030.18
Year	Operation Costs per year 1 turn (€)	345.60		Year 2	10102.81	31845.62
Year	Operation Costs per hour 3 turns (€)	1036.80		Year 3	9004.06	28770.25
Year	Maintenance/Inspection Expenses Daily Basis (€)	930.00		Year 4	8212.83	26182.09
3º Year	Maintenance/Inspection Expenses (€)	240.00		Year 5	7590.39	23926.09
4º Year	Maintenance/Inspection Expenses (€)	200.00		Year 6	6764.88	21615.51
6º Year	Maintenance/Inspection Expenses (€)	240.00		Year 7	6273.05	19773.62
8º Year	Maintenance/Inspection Expenses (€)	1200.00		Year 8	5142.96	17416.21
9º Year	Maintenance/Inspection Expenses (€)	240.00		Year 9	5082.56	16240.05
	Labor Savings per operator (€)	13500.00		Year 10	4713.04	14856.22
	Labor Savings per 3 turns (€)	40500.00		CashFlow Sum	73999.66	235655.85
	Discount Rate (-)	0.10		NPV	56399.66	218055.85

4.2. Payback Period Analysis

The Payback Period Analysis calculates the time it takes for an investment to recover its initial cost. The inputs required to perform this analysis include [15, p.388–389]:

1. Initial Investment Cost
2. Cash Inflows
3. Cash Outflows

By comparing the initial investment cost with the annual cash inflows, it’s possible to determinate the payback period, the length of time required for the project to recover its initial investment. The payback period analysis helps assess the time it takes to recoup the investment and provides insights into the project's profitability and risk.

It's important to note that the payback period analysis does not consider the time value of money or the profitability beyond the payback period. It is a simple metric used to evaluate the time it takes to recover the investment cost.

With all these variables defined in the NPV calculation it is enough to calculate the comulative cash inflow to determine when payback is expected, for the 1 turn scenario the expected payback is on the 2º year and for the 3 turns scenario the payback is on the 1ª year, with a profit of 21000 €.

4.3. Discussion of results

Based on the results obtained from the NPV and Payback Period Analysis, it can be concluded that the implementation of the robotic arm solution for the automation of the process is financially viable.

The NPV analysis revealed that for a 1-shift work schedule, the NPV was calculated to be 56,400 €, and for a 3-shift work schedule, the NPV was calculated to be 218,000 €. These positive NPV values indicate that the project's expected cash inflows exceed the initial investment, resulting in a net positive present value.

Additionally, the Payback Period Analysis indicated that the payback period for the project is expected to be on the 2nd year for the 1-shift work scenario and on the 1st year for the 3-shift work scenario. This means that the initial investment will be recovered within the specified time frames.

Considering these financial metrics, it can be concluded that the project is financially feasible and offers a favorable return on investment. The implementation of the robotic arm solution not only provides labor savings but also demonstrates the potential for long-term profitability and increased operational efficiency.

5. CONCLUSION

5.1. Final conclusions

Throughout the months of intensive work and analysis, this project has culminated in the development of a comprehensive solution centered around the implementation of the JAKA Zu 3s Collaborative Robot. The journey began with a meticulous assessment of project requirements, followed by consultations with Fluidotronica, a reputable company specializing in autonomous solutions. With careful consideration and evaluation, the JAKA Zu 3s Collaborative Robot was selected as the optimal choice for the project.

While the physical implementation of the robotic arm is yet to be realized, the financial analysis conducted has provided valuable insights into the project's economic viability. The Net Present Value (NPV) calculations have demonstrated positive outcomes, indicating that the project is expected to generate returns exceeding the initial investment. The NPV result of 56,400 € for the one-shift operation and 218,000 € for the three-shift operation further supports the financial feasibility of the project.

Furthermore, the Payback Period Analysis has revealed that the project is forecasted to recoup the initial investment within two years for the one-shift operation and within one year for the three-shift operation.

These results signify the project's ability to generate profits and validate the financial soundness of the endeavor.

5.2. Limitations and future work

Despite the success achieved, this project faced certain limitations and challenges along the way. One limitation was the availability of resources, both financial and technical, which influenced the scope and scale of the project.

Looking ahead, there are numerous prospects for future work and improvements. Once the JAKA Zu 3s Collaborative Robot is integrated into the workflow, continuous monitoring and optimization will be crucial to identify areas for further enhancement. Regular maintenance and potential software upgrades will ensure the robotic arm's optimal performance and longevity. Additionally, exploring advanced programming techniques and leveraging the collaborative features of the robot can unlock even greater levels of automation and efficiency.

In conclusion, the meticulous planning, expert consultation, and thorough financial analysis have resulted in a comprehensive solution centered around the implementation of the JAKA Zu 3s Collaborative Robot. With positive NPV results, substantial returns on investment, and a relatively short payback period, this project exhibits strong potential for success. While the implementation of the robotic arm is pending, the groundwork laid and financial analysis conducted provide a solid foundation for future implementation and demonstrate the project's viability. By harnessing the capabilities of the JAKA Zu 3s Collaborative Robot, this project has the potential to revolutionize the workflow, increase productivity, and drive economic growth.

Furthermore, the versatility of the JAKA Zu 3s Collaborative Robot extends beyond the current project, presenting opportunities for its application in other areas of Ficocables. With its advanced capabilities and adaptability, the robotic arm has the potential to streamline various processes, enhance efficiency, and contribute to the overall growth and success of the company.

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