Implementation and integration of a collaborative robot in a production line

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Degree Project

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Stockholm, October 2018
Implementation and integration of a collaborative robot in a production line
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"If I had asked people what they wanted
they would have said faster horses"

Henry Ford

to my sister

Anastasia
Preface

Trying to imagine how the factory of the next decades will look like, one thing is certain, it will have nothing to do with the factory of today, but probably not the way many expect. Ever since the 1st Industrial Revolution when mechanization spread, through the use of water and steam power, the labor work was replaced by machines. Each technological advancement and revolution – from computers and robotics to the internet – has led to more and more automation. Although many manufactures are applying “lights out factory” setups, a manufacturing methodology, where production is fully automated and little or no human intervention is required, the need of the human factor will never be obsolete. The previous statement is reinforced by the current consumer trend for more and more personalized and handmade products that reflect the human involvement and touch.

But how can both sides be satisfied, from one side the costumers that request more personilised products and from the other, the factories that they target to lower operational costs. The answer lies in providing technical capabilities, skills and training to the operators. Instead of loading or moving a part every 1 minute, doing a pepetetively boring task that does not add any value neither to him neither to the process, the operator, after the training, is able to collaborate with a robot, monitor it and even feel that the final product has his own personal touch. Although, in the short term, training your personel is a significant cost for the companies, in reality, in the long run, is an investment with a high rate of return. Highly trained employees that enjoy their work lead to better production processes, more productivity, more effectiveness, less scrap and finally less operational costs.

Despite many peoples’ fear that technology –especially robots– will eventually replace humans, history shows that technological advancements are job creators. It is true, however, that through automation some jobs tend to become obsolete –and thus likely to disappear– but in the other hand, new jobs are born that predominantly require less manual strength and more intellectual.

Customers demand qualitative, low cost and in the same time sophisticated products. This will neither be achieved by small traditional craftstores nor by large scale fully automated factories. In order to achieve mass personalized products highly trained operators are essential. Operators with expertise in a working area that will
add value to the product and to themselves is the future. Operators performing repetitive, boring tasks tend to be obsolete.

Companies that apply the philosophy and the methods of Industry 4.0, like the use of cobots, have better chances to develop and flourish in an ever-increasing industrial competitive environment.

This degree project deals with the implementation and integration of collaborative robot in a production line. The scope of this project degree is to present all the process and necessary steps performed in order to develop a project of this kind. The current thesis will include project management tools and techniques used, modifications that were performed from the original design in order to be operational, the different parts and devices that consist the installation, actions performed to guarantee the safety of the people as well as all the necessary paperwork connected to the installation of a new feature in the line.

In the 1st chapter the scope of the project is described. Moreover, the 5 phases of project management according to the bibliography are detailed presented. More in concrete, the initiation, the planning, the execution, the performance and control and the closing phase of the project are analysed. Subsequently, it is presented how the theory of project management was implemented during the project and what kind of tools and techniques were used.

In the 2nd chapter the 4 industrial evolutions, as well as a historic overview of the evolution of collaborative robots are presented. Furthermore, the potential and the future of the market of collaborative robots is described.

In the 3rd chapter the all the devices and elements that compose the project are presented in detail. More in concrete, the different working areas, the safety devices, the electrical and neumatic installation. Finally, the programming logic and sequence is elaborated step by step.

This thesis closes with the conclusions of the project. Also, future modifications and improvements that will facilitate the process are proposed.
Acknowledgements

I would like to express my sincere gratitude for the help and support throughout writing the current thesis:

My supervisor, Mr. Ove Bayard, PhD at KTH Royal Institute of Technology and programme coordinator at the Production Engineering and Management masters’, for his collaboration throughout the writing of the thesis.

Jesús Antón, start-up leader in Procter & Gamble and project manager of the project, for his patience, mentoring, motivation and meaningful discussions that made me to think critically. Without his proposition to involve into the project, the conduction of this thesis, would not be possible.

Andrés Perez, technical expert of the project, for his, help, guidance, support, encouragement, theoretical and technical support, but most important for his friendship.

Miguel Ferrandiz, installation manager in Procter & Gamble, for his instructive suggestions and his immediate technical assistance in all my concerns.

All my colleagues in Procter & Gamble for making my everyday work pleasant.

My sister, Anastasia, for her unconditional love and presence in crucial moments of my life.

My parents, Nikos and Kalliopi for providing me with continuous support and encouragement throughout my years of study and in my life in general.

My friends, for those unforgettable years in Stockholm, for all the joys and sorrows we went through.

To Ilia for her love and patience.
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Abstract

Scope of this thesis is the integration and implementation of a collaborative robot in the production line.

In the first chapter, the project is described, and its objectives, purpose, boundaries and requirements are defined. Moreover, the project management tools and techniques are presented. All the steps and procedures followed before the initiation of the project are analysed.

In the second chapter, the basic theoretical background necessary for a better understanding of the content of this thesis is presented. The history and development of collaborative robots, as well as the industrial evolutions are mentioned. The different types of collaborative robots and their importance in Industry 4.0 and current production are analysed.

The third chapter deals with the detailed description of the project. All the devices and equipment are presented thoroughly. The programming logic and working flow is explained.

In the last chapter according to the initial objectives, boundaries and requirements the success of the project is assessed. An analysis of how the installation of automate corrugate loader affected the production process is performed. Future changes, improvements and technical suggestions are discussed.

The ultimate goal of this thesis project is that the content in the thesis report will be used as a guide for future installations of same or similar type of robots. The aim is to avoid many of the mistakes made, due to rush decisions, lack of experience and communication between team members. The leaning curve obtained during the implementation of the project, can lead to more effective projects in the future.

Key Words: Collaborative Robot, Industry 4.0, Project Installation, Project Management, Project Development, Production, Project Integration.
Fokus för denna avhandling är integrering och implementering av en interaktiv robot i en produktionslina.

I det första kapitlet beskrivs projektet, och dess mål, syfte, gränser samt krav definieras. Dessutom presenteras verktyg och tekniker för projektledning. Alla de steg och procedurer som använts/följts innan projektet påbörjades har analyserats.

I det andra kapitlet presenteras den grundläggande teoretiska bakgrunden för att ge en bättre förståelse av innehållet i denna avhandling. Historien och utvecklingen av interaktiva robotar, liksom de industriella evolutionerna näms. De olika typerna av interaktiva robotar och deras betydelse i Industri 4.0 och nuvarande produktion analyseras.

Det tredje kapitlet innehåller en detaljerad beskrivning av projektet. Alla enheter och utrustning presenteras noggrant. Programmeringslogiken och arbetsflödet förklaras.

I det sista kapitlet utvärderas projektets framgång utifrån de ursprungliga målen, gränserna och kraven. En analys utförs av hur installationen av den automatiska laddaren för veckmaskinen påverkar produktionsprocessen. Framtida ändringar, förbättringar och tekniska förslag diskuteras.

Det slutliga målet för detta exjobbsarbete är att innehållet i avhandlingen ska användas som en vägledning för framtida installationer av samma eller liknande typ av robotar. Syftet är att undvika många av de misstag som gjorts, på grund av brådska beslut, brist på erfarenhet och kommunikation mellan lagmedlemmar. Lärandekurvan som uppnåtts under genomförandet av projektet kan leda till effektivare projekt i framtiden.

**Key Words:** Interaktiv Robot, Industry 4.0, Projektinstallation, Projektledning, Projektutveckling, Produktion, Projektintegration.
Chapter 1
Project Management

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1.1 Introduction

The development of Project Management was based on the need to plan, coordinate and control complex and various activities required in modern industrial and commercial projects. The purpose of Project Management is to anticipate and prevent future risks, failures and problems that could occur during the implementation (as well as during the planning and execution) of the project, as well as to achieve their completion within the time and financial frame that have been set [1].

Some common examples of project management are:


In the beginning, the current chapter describes the scope of the project. Then, the theory of project management and the triangle of success of a project are presented. The 5 phases of project implementation are described in detail. According to the beforementioned theory and the 5 phases, the project was developed. Moreover, the tools, techniques and processes used, during the implementation are presented.

1.2 Project Scope

The scope of the current project is the implementation and integration of a collaborative robot (cobot) in two production lines of diapers aiming at the automation of the production and the reduction of the workload of the operators.

The project is based on the existing solution applied in another plant of pads. The project includes the implementation of a Collaborative Robot (cobot), which automatically aliments the automatic case packer with boxes. The development of the project includes all the necessary modifications in order to achieve a smooth transition of the existing manual alimentation to an automated one. The developing team should provide the standards, the systems and the technical capabilities to the operating team of the production lines in order to be able to perform the necessary basic maintenance of the feature and validate new product references autonomously. More in detail, the project includes programming of the cobot, verifying the electrical and mechanical commissioning, apply the rules of safety and security that the Spanish law and the company requires, writing all the necessary documentation (troubleshooting guides, 2D designs, maintenance guides, guidelines for the operators etc), make all the necessary installation modifications in order to fulfill the needs of the project, configuration of the supportive equipment (sensors, QR code reader, security lasers, ultrasonic laser, digital controllers etc.), integration with the production information system of the lines. Moreover, the project includes collaboration with the external partners, responsible for the mechanical and electrical installation.
1.3 The Triple Constraint

Without any exaggeration, it can be stated that, to a great extend the success of a project depends on proper project management. Although it is often thought to be an extra cost on the budget, reaching sometimes even the 20% of the overall project budget, in reality is the connecting link between the triangle of successes, scope, cost and time. These three factors, commonly called the triple constraint ensure the success of the project.

The project manager needs to keep on track that the project will be completed within the time frame set from the beginning, the initial budget will not be exceeded, and the tasks required to fulfill the project’s scope will be performed. Is the one who unites teams and clients, keeps everyone on the same page and through proper management creates the roadmap to success [1].

Changing one of the above factors affects at least one of the other two. If, for example, the project has to be completed in less time than initially determined, it is very likely that there will be a cost increasement or unperformed tasks. The relationship of these three factors is shown on Figure 1.1 [2].

![Figure 1.1: Triple constraint between cost, time and scope](image-url)
These three factors are also the parameters of success or failure of a project. However, there are also secondary factors such as reducing the risks of implementation, monitoring and supervising the progress of the project, compliance with the company's overall objectives, making profit from implementation, acquiring know-how, increasing the quality of the offered services and products, etc.

A project can be considered successful if the following occurs:

- The project is delivered on time, as determined by the timetable. At the same time, at the project timetable the necessary resources have to be defined, since it is an important factor affecting the duration of the phases. It is therefore necessary to always draw up a proper resource management plan, through which it is planned the use of the resources throughout the project. Of course, before creating the resource management plan, all phases of the project must be identified.

- The cost of the project does not exceed its budget. A project must be implemented at the lowest cost over time, without discounts on the quality of the project. The budget of the project must be strictly adhered to at every phase. The actual financial assets of the project are related to resource requirements, pricing policies, budgeting, costing, and more.

- The quality of the deliverables has to be in accordance with the specifications. Quality determination is a difficult task but at least the functional requirements of the project, as well as performance requirements, must be met. Through a plan of quality, the quality goals and the methods to be followed to achieve these goals must be identified [3].

1.4 The Project Management Phases

The Project Management Institute (PMI) in order to facilitate the management of a project, has developed a process which consists of 5 phases (Figure 1.2). The division of a project into phases increases the possibility to reach the best possible outcome. Through this division into phases, the total work load of the project is divided into smaller tasks, thus making it easier to monitor. The 5 development phases of a project are the following [4], [5]:

Degree Project - 4 - Emmanouil Bafounis - Kottas
1.4.1 Initiation

This is the start of the project, where its foundations are set. The goal of this phase is to give a broad definition of the project. First of all, a feasibility research has to be conducted, clarifying if the project is viable and should be undertaken. Moreover, the value that the project will return to the company has to be clearly defined, the time duration and draft cost have to be calculated. Another critical task is to get the approval from the board or the stakeholders to initiate the project. When the green light has been given, a project charter has to be created. A project charter is a statement of the participants, objectives, and scope in a project. It serves as a preliminary definition of roles and responsibilities, outlines the project objectives, identifies the main stakeholders, and defines the authority of the project manager.

1.4.2 Planning

This phase starts with the creation of a primary project management plan. This plan serves as a roadmap and an implementation guide, where all the necessary elements and goals to succeed are described. It also includes an organizational chart, a detailed description of the tasks to be performed, a detailed cost, identification of available resources and creation of a realistic timetable, calculation establishment of baselines and performance measures. Furthermore, the deliverables have to be identified and defined. These are all the products, documents or services that will be
delivered to the project sponsor at the end of the project. Moreover, a baseline is established, which determines if the project is on track and the Project Manager clearly defines the responsibilities and the roles, so everyone evolved knows what is accountable for.

During this phase certain documents have to be created. These are the following:

i. **Scope Statement**: in this document the project’s needs, objectives, deliverables, tollgates and milestones are clearly defined. A tollgate is a control point/date where the project progress is reviewed and audited if necessary. The tollgate is used to verify if the project is on track. A milestone are points/dates that mark the start or finish of a phase. During the project implementation, the scope management can be edited, but only through the approval of the sponsor and the project manager.

ii. **Work Breakdown Structure (WBS)**: is the process of decomposing project deliverables, tasks and work into smaller, more manageable components. It is a hierarchical description of the work that must be done to complete the project as defined in the specification. It is preferably performed by the project team and focuses on the tasks required to produce the artifacts that are to be delivered.

iii. **Gantt Chart**: is a visual timeline, where you can plan out tasks and visualize your project schedule. This chart lists the tasks to be performed on the vertical axis, and time intervals on the horizontal axis. The duration of each activity is shown by the width of the horizontal bars of the chart. The Gantt chart illustrates the start and finish dates of the different tasks and summaries the tasks of a project.

iv. **Communication Plan**: defines how critical information will be delivered throughout the project, by who, and at what frequency. How the communication plan will be structured is based on the deliverables, the tollgates, the milestones and the different stakeholders.

v. **Risk Management Plan**: A short analysis, where all foreseeable risks that can delay the project are identified, and an action list on how to avoid these risks is created. Common risks include change of requirements, unrealistic cost and time estimates, budget differentiations and lack of resources.
1.4.3 Execution

This phase usually starts with a kick-off meeting, organized by the Project Manager including all the involved members and teams. During this meeting the Project Manager discuss the project in detail with the team, presents the milestones, the tasks to be performed and inform them about their responsibilities.

This is the phase where deliverables are developed and completed. It is probably the most stressful period of the project, since a lot of actions are happening, like, tasks assignments, installations, developments, status reports and meetings, progress updates, and performance reports.

1.4.4 Performance and Control

This phase is conducted in parallel with the 3rd phase of the project execution. During this phase the project manager monitors the progress and the performance of the project to avoid derailment of the project. To ensure project’s alignment with the initial project management plan, Key Performance Indicators (KPIs) are used. KPIs are performance measurements that demonstrate how effectively a company is achieving its key objectives. The companies use key performance indicators at multiple levels in order to evaluate their success at reaching their targets. During this phase, is very common that the project manager has to adjust schedules and resources to ensure the alignment of the project.

1.4.5 Closing

This phase represents the completion of the project. The project manager is responsible to create a punchlist of tasks that were left unaccomplished and argument the reason. Moreover, a final report has to be written, including the final budget and all the necessary documentation has to be completed. The sponsor of the project has to approve all the deliverables.

Once the project has been completed, the project manager holds the post mortem meeting, where is evaluated what went well in the project and project failures are identified. This meeting serves as a learning curve in order to make improvements for future projects. The members of the team are redeployed to their usual work. The project manager organizes a celebration/closing party with all the team members [6], [7].
Chapter 1
Project Management

1.5 Project Management Implementation

1.5.1 Initiation Phase

The current project started with a financial analysis of the imminent investment. The financial calculation was performed for the next 5 years. The initial investment was 174,300 €, which includes the installation of 2 cobots in 2 production lines. The Net Present Value (NPV) of the investment over a period of 5 years and an initial investment of 174,300 €, was calculated to be 346,000 > 0, which indicates that the investment will be profitable and worths to do it.

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Annual Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018 - 2019</td>
<td>202,400 €</td>
</tr>
<tr>
<td>2019 - 2020</td>
<td>154,080 €</td>
</tr>
<tr>
<td>2020 - 2021</td>
<td>156,390 €</td>
</tr>
<tr>
<td>2021 - 2022</td>
<td>158,740 €</td>
</tr>
<tr>
<td>2022 - 2023</td>
<td>161,120 €</td>
</tr>
</tbody>
</table>

Table 1.1: Cash inflows over a period of 5 years

The next step was the creation of the project charter.
## Issue Statement

Describe the process to be improved or problem to be solved. Give some background information.

The mission of the project team is the implementation of a Collaborative Robot (cobot), in lines D1 and D7, which will automatically aliment the automatic case former with boxes (vs the current manual alimentation), as well as providing the standards, systems and technical capabilities to the equipment of these lines that will allow the maintenance in base conditions of the Cobot and train the line teams to validate new references autonomously.

It is a **local development** project that pursues the following objectives:

- Elimination of the material feeder (0.5 Full Time Employee (FTE) per line and shift)
- Reorganization of the glue alimentation team
- Integration of the Cobot in the systems of the lines

## Key Package Changes

- All the paquetes of the boxes should have 2 straps.
- The cardboard separator in the palets should be removed.
- Possible material change of the strap in case the ejectors cannot aspire it.
- The installation of the automate corrugate loader does not require any changes to the existing equipment of the line. All the installed equipment is independent and no changes in the packaging machines will be made. The cobot will be integrated in the software of the line.

## Major Process & Equipment Scope

The project includes the creation of a new feature (805) for the automatic alimentation of the boxes.

In a simple way, the Cobot is divided into the following areas (or sub-features):

**End Effector:** Grabs the boxes and transports them from the pallet to the workstation. The gripper adjusts according to the size of the box.

**Robotic Arm:** The arm allows 5 axes movement.

**Workstation:** It is the area where each package of boxes is placed to remove the straps. Two wedges are used to engage the straps. Then, two blades cut the straps,
which are removed by 2 venturi ejectors. The scrap straps are stored in a container outside the feature.

<table>
<thead>
<tr>
<th>Desired Results with Success Measures</th>
</tr>
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<tbody>
<tr>
<td>What is the expected outcome of the team?</td>
</tr>
<tr>
<td>What are the business results expected?</td>
</tr>
</tbody>
</table>

i. A safe and secure feature. Zero injury incidents during the installation phase, as well as during its normal operational conditions should occur. To achieve that, all the necessary procedures and rules have been followed. During the installation phase, before performing any task, a risk assessment document has to be filled in and signed, which describes all the possible risks and the countermeasures taken. Also, all the possibly unsafe areas are indicated with caution sings and include protection. During the operation of the automate corrugate loader, the operators are obliged to deactivate the current and the vaccum, in case they want to acces the feature. Moreover, detailed lockout matrices and instructions have been written, describing how minor and major servicing should be performed.

ii. Quality assurance. Zero quality issues and claims related to packaging, neither from the customers nor from the other departments of the company. The success of the process should also lead to zero quality inspections.

iii. Full use in all references. The automate corrugate loader should be able to handle 100% of the fabricated references, which should have been validated until the end of September.

iv. MTBF (Mean Time Between Failures) ≥ 120 min. That means that the automate corrugate loader should be able to operate autonomously, for at least 120 min, without any interruption. The time of 120 minutes corresponds to an entire palet.

v. No impact on the material scrap. During the installation and operation phase, the material utilization tracker (MUT) should not be affected.

vi. The implementation of a new reference should last less than 2 hours. It includes the calculation of the required values, the documentation and the integration to the software of the line.

vii. The validation of a new reference should last less than 2 hours. To achieve that, detailed instructions have been composed, assisting and simplyfying the validation procedure. The timeframe of 2 hours validation corresponds to the alimentation of an entire palet, which consists an objective sample in order to extract safe conclusions.
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- viii. The Gross Manufacturing Cost (GMC) of the project should not exceed 20,000 €. All necessary modifications to the equipment that need to be made, are being carefully considered, economically and technically, before they are carried out.

### Tracking System & Reviews

How will the team track its progress? When, how & by whom will the work be reviewed?

<table>
<thead>
<tr>
<th>Process Measures (In-Process):</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ The progress of the team is tracked through the Global Start Up Management (GSUM) tracker once per week. Responsible for this task is the Start-up Leader (SuL).</td>
</tr>
<tr>
<td>➢ The progress of the construction and installation is tracked through the construction readiness tracker once per week. Responsible for this task is the Construction Leader and the Start-up Leader.</td>
</tr>
<tr>
<td>➢ The progress of the deliverables is tracked through the Seamless Technical Organization (STO) Local Tracker, once per week. Responsible for this task is the Start-up Leader, the Operating Department Manager (ODM) and the Operations Manager (OM).</td>
</tr>
<tr>
<td>➢ The shutdowns of the Case Erector (daily tracking using Proficy software, by failure mode and by Finished Product Code).</td>
</tr>
<tr>
<td>➢ Executing Current Operation Assessment (COA) (Case Erector).</td>
</tr>
<tr>
<td>➢ Using the Project Loss Analysis Tool (PLAT) in the 1st installation line to collect knowledge for the rollout of the other line.</td>
</tr>
</tbody>
</table>
In order to define the boundaries of the project, the Pilar methodologies of IM Project Management, the Capital Management and the GSUM are used. Following the above tools

The best standards created by the other plant are used and applied to our plant by integrating them into the rest of the line end.

- We define roles in each phase of the project and ensure the adequate skills to do the job well.
- The COBOT is one more feature of the line (805) and as such, has the same treatment: assigned equipment owner, allocation of stoppages and unplanned PR loss. It has RLS, Run Route and maps of cleaning, lubrication, Time Based Maintenance (TBM) and Troubleshooting (TBS) guide.
- The Technology Transfer & Training member of the team (TT&T) is focused on creating experts in the lines of this technology, with a task-based approach to training. The training and qualification in based on Step-up cards (security, operation, process and problem solving).
- The validation capacity of new references should be transferred to the line teams.
- We establish plans, via Current Operation Assessment, that allow us to execute the project in the best condition:
  - Daily Direction Setting (DDS) Health check > 85%
  - Results: in a sustained manner, in the last 3 months before the implementation (focus on stoppages per day of the automatic case former)
  - Conditions (automatic case former): lines in the base conditions (equipment, process and software), Daily Management Systems (DMSs) Clean, Inspect, Lubricate standard (CIL), DH (Defect Handling) and Corrective Maintenance (CM) in automatic case former > 85%
  - Behavior: the plans are aligned, respected, protected and executed.

DRUM BEAT:

Objective: Visualize the intermediate measures to pull the leadership, eliminate barriers, and help the preparation of the team on a weekly basis.
# Resources / Responsibilities
What resource is given to the team to achieve the Desired Results?
Name the Team Leader, team members, consultants (if any), and the Sponsor

<table>
<thead>
<tr>
<th>Name</th>
<th>Function</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CORE TEAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.... G....</td>
<td>Project Sponsor</td>
<td></td>
</tr>
<tr>
<td>R.... M....</td>
<td>Project Leader</td>
<td></td>
</tr>
<tr>
<td>L.... O....</td>
<td>Capital Manager</td>
<td></td>
</tr>
<tr>
<td>L.... O....</td>
<td>Construction Manager</td>
<td></td>
</tr>
<tr>
<td>M..... F.........</td>
<td>Technical leader</td>
<td>P&amp;E Deliverables</td>
</tr>
<tr>
<td>G...... S....</td>
<td>MSDO</td>
<td>Processable pallets with scrap y effort = 0</td>
</tr>
<tr>
<td>J..... A.....</td>
<td>Start up leader</td>
<td>IQOQPQ, S/u Plan Mnf Success criteria</td>
</tr>
<tr>
<td>Andrés Pérez</td>
<td>TT&amp;T leader</td>
<td>Manufacturing Deliverables CQV Leader</td>
</tr>
<tr>
<td>JA. P...... (A. M....)</td>
<td>HSE</td>
<td>D&amp;C Checklist</td>
</tr>
<tr>
<td>P.... G....</td>
<td>Tier 1 SPOC &amp; MEAT</td>
<td>Team Model, MEAT, EAP</td>
</tr>
<tr>
<td>Ó...... G......</td>
<td>EA6/10 Equipment Owner</td>
<td>Deliv Manuf EA6</td>
</tr>
<tr>
<td>M...... C.....</td>
<td>FemCare SPOC</td>
<td>CQV Leader</td>
</tr>
<tr>
<td><strong>EXTENDED TEAM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J...... N......</td>
<td>SEAO EA4</td>
<td>Deliv Manuf EA4</td>
</tr>
<tr>
<td>J..... B......</td>
<td>E&amp;I</td>
<td>Proficy RE + RTT integration</td>
</tr>
<tr>
<td>J..... A..... P....</td>
<td>E&amp;I</td>
<td>Deliv Manuf P&amp;C</td>
</tr>
<tr>
<td>M..... T.....</td>
<td>BAM</td>
<td>Staffing assurance</td>
</tr>
<tr>
<td>J..... M.....</td>
<td>Line Lider D1</td>
<td>RLS + Run Route</td>
</tr>
<tr>
<td>M...... O......</td>
<td>Line Lider D7</td>
<td>Cleaning Maps</td>
</tr>
<tr>
<td>J...... S......</td>
<td>Line Coordinator D1</td>
<td>TBM COBOT</td>
</tr>
<tr>
<td>A...... C......</td>
<td>Line Coordinator D7</td>
<td>Lube maps</td>
</tr>
<tr>
<td>D..... C.....</td>
<td>PSC SCO/RCO Leader</td>
<td>SCO Checklist</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SCO qualification plan</td>
</tr>
<tr>
<td>F..... G......</td>
<td>Site Manager</td>
<td>Layout</td>
</tr>
<tr>
<td>A...... M......</td>
<td>HS&amp;E Manager</td>
<td>Change Control</td>
</tr>
<tr>
<td>J.... L.... L.....</td>
<td>QA Standards Office</td>
<td>Validation data sheets. QA SPOC</td>
</tr>
<tr>
<td>P..... C.....</td>
<td>Storeroom Leader</td>
<td>Parts Supply leader</td>
</tr>
<tr>
<td>C..... G......</td>
<td>SIEL</td>
<td>FPC s/u sequence</td>
</tr>
<tr>
<td>M...... H......</td>
<td>CyberSecurity Leader</td>
<td>IT tools integration (e-DH; peCIL)</td>
</tr>
</tbody>
</table>

## Agreements

<table>
<thead>
<tr>
<th>Sponsor: C..... G.....</th>
<th>Plant Manager</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cliente: C..... H......</td>
<td>Operation Manager</td>
</tr>
</tbody>
</table>
1.5.2 Planning

During this phase different organizational charts were created, less or more detailed. The first chart created was the Critical Path Schedule (CPS) (Figure 1.4). This chart is used to facilitate the understanding of the required inputs and outputs of the project. Moreover, facilicates the interactions of the Start-up Leader with the project team. A CPS is not a very deep and detailed chart, but a general wide plan that provides a general picture of the project.

**Figure 1.4:** Critical Path Schedule (CPS)

Another useful chart used, was the construction plan, which is an overall plan of how construction work will be contracted and managed. The construction plan is updated as the construction team obtains additional project details (Figure 1.5). In the construction plan all the different tasks are described and scheduled to be performed in a defined date. The construction plan consists of three different levels of detail, the Level 0, where every task is assigned to a date, in a time scale of 3 months. The Level 1, where the tasks of Level 0 are described in a time scale of 1 day. The Level 2, where the tasks of Level 0 and 1 are divived into subtasks in a time scale of 1 day.
Global Start Up Management (GSUM): It is a tool developed by the company in order to improve startups. GSUM is a key process to enable Vertical Start-Up (VSU). VSU is a term used to describe the speed in which a project goes from installation to full production. VSU facilitates a new startup to deliver more than 85% Process Reliability (PR) within 2 months of the start of production. It is a tool that saves time, raw materials/scrap, and boosts production capacity.

GSUM can be applied to situations when:

- New equipment is added to an existing system.
- A new facility is provided at an existing site or at a new site.
- An existing equipment is added.

Purpose: develop of a comprehensive/integrated plan and ensure the plan is executed successfully. This plan includes all the activities related to the equipment, people, materials and technical systems.

Objective: ensure that the equipment, people, material and technical systems are ready to achieve the predefined Project Start-Up success criteria and to sustain ongoing target performance.
GSUM defines the right work at the right time, clarifies operation’s role/ownership in start-up, increases the level of rigor, reduces start-up risks by identifying gaps early, reduces total effort by defining ownership and driving timely execution tasks, focuses on initiative and operational readiness.

Through GSUM tracker all the necessary tasks to be performed are listed and organized. Each task is assigned to a specific person and its timing is determined. The duration of each task is added on the GSUM tracker, as well as how soon before a key date the task needs to be done. Furthermore, the GSUM tracker warns the project manager when the task should be started, then its almost due and when is overdue.

On Figure 1.6 the blue curve defines the percentage of project’s completion in order to be on track. The red dots represent our current status on the project’s completion.

![GSUM+ on time Readiness](image)

**Figure 1.6: GSUM Tracker Graph**

Furthermore, during this phase all the required deliverables of the project are defined, and the relative folders are created. Some of the deliverables are, software backups, mechanical and electrical drawings, troubleshooting guides, step-up cards, lubrication and clean, maps, security guides, operation instructions, loss allocation documents, failure mode trackers, pre-start-up inspection documents etc. The progress of the deliverables is tracked by the Seamless Technical Organisation (STO) tracker (Figure 1.7). The STO tracker is renewed once per week by the Start-up leader. At the end of the project the sponsor has to approve all the deliverables.
Then, a risk assessment was conducted. The risk assessment includes the item that will be assessed, where is located, what type of hazard can cause (mechanical, electrical, thermal, etc), the hazard’s origin, its severity, its probabiliblity, its risk level (red, yellow, green), how this hazard can be handled and the final risk level after the necessary protective actions. In Figure 1.8 the risk assessment is presented.

The system is designed such that all human interfaces with the system are outside the safety rated area limits of the robot. The robot system shall be stopped prior to human entry into the area for maintenance or correction of system malfunctions. The robot working area is clearly ‘defined with floor markings. Humans can only enter the active working area of the robot in the case of intentional misuse of the system.
Then, a time analysis regarding the change in the work load was performed. Since the material feeder will be substituted by the cobot, some tasks previously performed by the material feeder need to be transferred to the operators of the line. More specifically the responsible operator is the one that works in area 4. The initial time spent for this task by the operator before the implementation of the cobot was 5.6 minutes per shift and the predicted time will be 56 minutes per shift. How the analysis was conducted is presented in the Figure 1.9.
The cardboard covers that cover the upper area of the pallet are removed.

The IRMS of the raw material to be entered in the box former is checked.

The pallet arrives at the start of the line from the warehouse.

The raw material labels are removed and a copy is saved.

The pusher plates are placed in the box former.

The two straps that maintain the structure of the pallet are removed.

The separating cartons between the packages are removed.

The retractable plastic that protects the pallet is removed.

The empty pallet that is located next to the box former is carried to the line start.

Figure 1.9: Work Load Analysis

The communication plan that was created includes weekly meetings that involve matters like security, quality, spare parts and define who is responsible for their organization. The communication plan is presented on Table 1.2.

Table 1.2: Communication Plan

<table>
<thead>
<tr>
<th>Core Team</th>
<th>Security</th>
<th>Quality</th>
<th>Spare Parts</th>
<th>SIEL</th>
<th>Louveira</th>
<th>OPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>JA</td>
<td>JA</td>
<td>JA</td>
<td>JA</td>
<td>CG</td>
<td>JA</td>
</tr>
</tbody>
</table>

1.5.3 Execution

During the execution phase and more in concrete, during the Operation Qualification, the process is divided into subprocesses, which facilitate the identification of failures. Identifying the failure is the first step, in order to distribute
the necessary resources, time and effort to solve it. In Figure 1.10 are presented the subprocesses of qualifying the programmic logic.

![Figure 1.10: Subprocesses Qualification](image)

Since the current project is not a rollout, but requires local development and modifications, another tool was used to ensure its success. The top 5 risks of the process were identified and analysed (Figure 1.11). This document includes the identification of the risk, the description of the failure mode, the owner/responsible of finding a solution, the action that will be performed, its status, the result of the test and any necessary assisting documentation or link.

![Figure 1.11: Top 5 Risks](image)

Another useful tool used during the execution phase of the project is the issue tracker. The issue tracker is a document, where all the issues/troubles/problems presented during the installation were recorded and analysed in order to be solved (Figure 1.12). The issue tracker includes, the area where the issue occurred, the date, the type of issue (mechanical, electrical), its description, its cause, in which phase of the project occurred, the actions that will be made, the responsible to perform the
action, its current status, date of action and actions that will ensure that the same issue will not repeat in the future.

Figure 1.12: Issue Tracker

1.5.4 Performance & Control

In order to monitor the performance of the project an efficiency tracker was created. In this tracker the process has been divided into different tasks performed during the execution of a cycle. Every task corresponds to a possible loss. The analysed period is one entire month. Since one of the success criteria of the project is the Mean Time Between Failures (MTBF) must be more than 120 min, the efficiency tracker has been created in order to measure this index. Moreover, in this tracker every loss has a percentage frequency in respect to the total losses during the month. Moreover, the uptime and the downtime can be tracked. The efficiency tracker is presented on Figure 1.13 and Figure 1.14.

Figure 1.13: Efficiency Tracker
A very useful tool used to ensure that the equipment meets its base conditions of operation is called Critical Process Equipment (CPE) (Figure 1.15). The CPE’s are guidelines and instructions of the different adjustments of the equipment. They are process calibrations and process settings that are unable to be measured on the run. These checks intend to ensure product variable and targets maintained. The CPE’s are set during the equipment commissioning and are used as part of deep problem solving.

Figure 1.14: Efficiency Tracker Graph
In order to be able to track failures of the installed equipment, another document has been created, called Breakdown Elimination (BDE) (Figure 1.16). Through that document, useful data can be collected regarding the frequency of the failure, defining if it is a common or a random failure. Since, this is a global document used by all the plants working with the same technology, the collected sample is quite wide, enabling to draw more objective conclusions.

Figure 1.16: Breakdown Elimination

Another useful index that will be used in order to evaluate the performance of the new feature is its comparison with the performance of the line before its implementation. To achieve that, productions reports of the last three months with all the fabricated references have been exported. The reports refer to the stops at the end
of the production line and at the box former machine. The results will be later compared with the results after the full integration of the project.

1.5.5 Closing

This phase of the project management has not started yet since the project is between the execution and the performance and control phase. The estimation for this phase is planned for the end of the calendar year 2018.

Nevertheless, all the lessons learnt during the implementation of the project will be presented in the conclusions paragraph of chapter 4. A preliminary evaluation of the positive and negative actions performed will be analysed. Furthermore, in the same chapter in the paragraph of improvements and suggestions, possible modifications that will improve the process, will be presented in order to be considered in future implementations. Their possible integration requires further analysis and investigation from the project team.

1.8 Chapter Summary

In this chapter both the project management theory as well as its implementation were presented. The 5 steps of project management were detailed described and analysed. Moreover, all the different tools used during the implementation of these 5 phases were presented.

The next chapter presents the 4 industrial revolutions, the importance of collaborative robots on Industry 4.0 and the market growth of collaborative robots in the next few years. Moreover, a short historical overview, regarding the development of collaborative robots is presented.
References


Chapter 2
Collaborative Robots & Industry 4.0

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2.1 Introduction

In the years to come, many predict that robots will take our lives and displace the last workers in the manufacturing sector. In economic terms, they predict that the shift will be similar to the transformation of the US economy from agriculture to heavy industry.

Census data show that over 50% of America's total population was employed in agriculture in the early 20th century. The rapid mechanization of agricultural processes and the development of manufacturing and services have decreased this figure to around 2%. As a result, many predict that such profound changes will occur
from a new revolution of robotics, as the new robots displace the last human workers in factories.

Collaborative robots can fill this gap. At the cost between $20,000 and $25,000, collaborative robots are significantly cheaper than traditional industrial robots and require only 3-5 years to depreciate them. They also have a relatively simple programming interface and can be easily used in different areas of a production line. Unlike conventional robots, they are safer, and can be programmed to recognize and learn from their mistakes.

This 2nd chapter presents the basic theoretical background necessary for a better understanding of the content of this thesis. The history and development of collaborative robots, as well as the industrial evolutions are mentioned. Furthermore, the different types of collaborative robots and their importance in Industry 4.0 are analysed.

2.2 Collaborative Robots

A collaborative robot or cobot is a new type of robot designed to work hand in hand with the human factor in a shared workspace, supporting and relieving him on his day to day job. Unlike to conventional industrial robots, who are designed to operate autonomously in a protective environment and were on fashion, until the last decade. Cobots were invented relatively recent, in 1996 by Michael Peshkin and J. Esward Colgate, professors at Northwestern University. Initially, the first cobots were emphasized mainly, on safety, providing the possibility of cobots and humans to work side by side. At this moment, they offer easy installation and integration, lightweight structure and ease of programming, making them easy to handle by the majority of the people, including the operators [1], [2].

The history of cobots starts on the late 1990s, involving a collaboration between the automotive company General Motors and the Northwest University and the University of California Berkeley. General Motors and in general the automotive industry, was facing a serious ergonomic problem. Work injuries and fatigue, due to heavy load tasks, were leading to work absence and were affecting the production line. Lifting and assembling a 4 kg shock absorber, it may not sound like a heavy task,
but imagine doing that 60 times every day, 250 days a year, equals repeating the same motion 15,000 times per year, causing body pain.

The story of Collaborative Robots started when the Occupational Safety and Health Administration (OSHA), a federal agency of the United States that regulates workplace safety and health, stated its concerns on how the ergonomic issues, in the automotive industry, that the workers face, were taken into serious consideration by the companies. Since General Motors was the leading market player, OSHA said that they should be the ones trying to find a solution. General Motors assigned this task to Steve Holland, head of General Motors, robotic department and Jim Rucker, head of General Motors General Assembly Center, who seek assistance from the professors Michael Peshkin and J. Eward Colgate of Northwestern University, as well as from professor Homayoon Kazerooni, of University of California, Berkeley. The result of this effort was called Intelligent Assist Device (IAD) (Figure 2.1) and is the ancestor of cobot. The IAD, is an industrial manipulator that allows the operator to handle any load with less effort, within the working area of it. The IAD cannot be considered as a cobot, since it cannot be programmed and work autonomously and requires the guidance of the human hand [3].

![Figure 2.1: Electronic and Pneumatic Intelligent Assist Devices](image-url)
2.3 Categories of Cobots

According to ISO/TS 15066 standard, which specifies the safety requirements for collaborative industrial robot systems, collaborative robots are divided into 4 main categories [4].

2.3.1 Safety Monitored Stop

This type of collaborative robots is designed to work autonomously and independently, with limited or zero intervention by the human factor. Through their advanced proximity sensing technology, when the presence of a human is detected they cease their operation and pass on standby mode. When the person, moves away they automatically resume their operation. Conventional industrial robots can be considered as safety monitored stop cobots with the addition of the aforementioned sensing technology.

2.3.2 Speed and Separation Monitoring

This category has many similarities with the safety monitored stop. This type of cobot is used in applications where more frequent human intervention is required. It includes a laser vision system, which enables the cobot to sense human’s proximity. As long as it detects someone approaching, it will deaccelerate its operation, stopping in case someone gets too close. As the operator is moving away from its working area, the cobot will accelerate little by little, until it reaches its normal working speed.

2.3.3 Hand Guiding

Are used predominately for pick and place applications. The technology that the end effector of the cobot carries, allows the operator to teach it a path, by guiding it through a sequence of motions. The cobot is capable of sensing its current position and read the forces applied to its end effector.

2.3.4 Power and Force Limiting

This category of collaborative robots is claimed to be the authentic one, since on the other three categories we can use regular industrial robots and transform them to collaborative, by using appropriate sensors. This category can be divided
into 3 subcategories:

2.3.4.1 Joint Sensing

It is the most common type of power and force limiting cobot. By using the current of their motor or force-torque sensors embedded in their joints, they can monitor the forces applied to their body. The operator can easily adjust the sensibility of the cobot by changing its speed, force, power and moment.

2.3.4.2 Force Sensor Base

In this case the cobot does not have embedded sensors in each of its joint, but only at its base. A large force-torque sensor installed at the base of the cobot assists to feel and monitor the different forces applied to its body. This type of cobot is very useful, since it enables the transformation of already installed robots to cobots. In that way, an investment of a new cobot is not required, the same software can be used and no changes in the layout of the plant is necessary. Moreover, while most of the cobots have a maximum payload potential of 10 kg, the force sensor base ones can lift up to 35 kg, widening their range of use in more applications. Robotic companies that use this kind of technology are Fanuc and Comau.

2.3.4.3 Skin Sensing

This is the most recent developed type of collaborative robot. Although its use is not widely spread, it is considered as the safest one for the human. Through a capacitive sensor system, the cobot can detect a human approaching within a radius of 20 cm and cease its operation, if there a threat of collision. The sensor is able to monitor the conductivity of the robot’s body and make it stop even before hitting something or someone.

2.4 Industrial Revolutions and Industry 4.0

The 1\textsuperscript{st} Industrial Revolution (18\textsuperscript{th}-19\textsuperscript{th} century), started from Great Britain and took place in central Europe and America. The invention of steam, the mass use of coal and the development of machine tools led to significant transition to the manufacturing processes. During this period, agrarian and rural societies became industrial and urban, and hand production methods were replaced by machines. The
2\textsuperscript{nd} Industrial Revolution (1870-1914), usually mentioned as technological revolution, happened a few years later and is characterized by the growth of pre-existing industries and the development of new technologies. The most significant invention of that period was the electricity that led to mass production. The 3\textsuperscript{rd} Industrial Revolution (1980-Present), also referred as the Digital Revolution is connected to the advancement of technology. Includes the use of computers, electronics, robots, automation in the production and the transition from analog electronic and mechanical devices to digital ones.

Industry 4.0 is a term used to describe the transformation of the traditional manufacturing to automated plants with self-monitoring machines. It includes cloud computing, data exchange, cyber-physical systems, the Internet of Things (IoT) and cognitive computing. In Industry 4.0 computers and automation are linked in a new way, combining the Internet world with the world of industrial production (Internet of Things). Decisions and monitoring of the operations of a factory are made via internet.

Regularly referred as the 4\textsuperscript{th} industrial revolution, industry 4.0 aims to convert traditional factories to “smart factories”, by using cyber-physical systems, which monitor the plant’s physical processes and make decentralized decisions. The robots are connected remotely with computer systems, equipped with machine learning algorithms, which control and instruct the robots with minimal inputs from the operators.

The term "Industrie 4.0" was first mentioned in a German memo in 2013. This memo is presenting a plan of how to fully computerized the production industry without the need of human involvement [5], [6].

The characteristics given by the German government for Industry 4.0 are:

- Strong adaptation of products according to flexible (but also mass) production.
- Improvement of the required automation technology by introducing methods of self-optimization, self-regulation, self-diagnosis and cognitive function.
- Support of the employees in their increasingly complex work.
The purpose of Industry 4.0 is physical systems to communicate and collaborate with each other as well as with the human factor (operators) in real time via a wireless network.

**Figure 2.2: The Industrial Revolutions**

The revolution of the manufacturing industry is reflected on Figure 2.2. Figure 2.3 is illustrating how the industrial revolution in collaboration with the human needs, have transformed manufacturing. Before the 1st and 2nd Industrial Revolutions through craft production, the customer was offered the desired product but at a high cost. Through the first two industrial revolutions and the introduction of the assembly line the customers were able to enjoy low lost products, but in small variety. After the 3rd Industrial Revolution the industry was able to provide mass variety of products without increasing significantly the cost of production. Industry 4.0 emerged in order to satisfy the need of the customers for personalized services and products.
There are four design principles that facilitate enterprises to implement and integrate Industry 4.0:

- **Interoperability**: The ability of sensors, people, machines and devices to connect and communicate with each other via the Internet of Things and Internet of People.

- **Information Transparency**: The ability of information systems to create a virtual copy of the physical world through sensor data for the purpose of making that information accessible to machines.

- **Technical Assistance**: The ability of systems to help and support the human factor by gathering and displaying comprehensible information for making informed decisions and resolving urgent problems in the short term.

- **Decentralized Decisions**: The ability of natural cyber systems to make decisions and perform their tasks as autonomously as possible.

**Figure 2.3**: The Manufacturing Evolution
2.5 Cobot

Never before in the 70-year history of robotics a machine has dominated so fast and easy the market, like this lightweight, agile, robotic arm, called cobot, did. Its wide range of applications in collaboration with its relatively low cost and its easy programming have made it extremely popular on global scale. Although, cobots its an emerging technology, still developing and expanding, companies of every field, are investing on them, installing them into their facilities. The considerably advancement of cobots over the last five years, in conjunction with the various cobot manufacturers are helping to push the price down and expand their use.

Many multinational companies, in order to stay ahead technologically and in relation with their competitors are investing on cobots. In that way, they can reduce their working cost, increase their productivity and quality and in the same time enhance the safety of their employees.

Such an example is the automotive company, BMW, which has installed 4 collaborative robots, which perform quality inspection to the cars. When the bonnet the trunk and the doors have been assembled to the main body of the car, 4 collaborative robots, equipped with cameras, as end effectors, inspect the existing gap, sending feedback to a screen, monitored by an operator. The conventional way included 2 operators using a caliber and inspecting little by little the entire car.

Another company, investing in cobots is Whirlpool. Although, Whirlpool historically is known for its conventional production lines, recently, installed more than 50 cobots that replaced repetitive, no adding value tasks. The cobots installed, are used to apply glue and sealants, as well as picking and placing components.

Some of the advantages that cobots offer, like ease of integration, adaptability, space-saving, flexibility, safety, easy programming, and cost efficiency make it extremely desirable [7], [8].

A research conducted by Barclays demonstrates the cobot market growth expected in the next few years. More specifically, by 2025 the global marketplace will be $11.5 billion (Figure 2.4), which corresponds almost to the size of the entire industrial robotics market today.
Another very interesting graph, also conducted by Barclays, demonstrates the difference between the labour cost in a developed European country, like Germany in comparison with the cost of a robot (Figure 2.5). The operational costs of a company can be reduced up to 7 times, by investing to a robot. Even in China that the manual labour cost is quite low, remains almost two times higher than the cost of a robot.

Figure 2.4: Global Cobot Marketplace

Figure 2.5: Robot & Labour Cost Comparison
Robots are rapidly emerging, threatening the global workforce. As the technology advances more and more jobs will be replaced by robots. In the next 4 years 6% of the jobs in America will be automated. But, what are the main differentiations between the human factor and a collaborative robot?

On Table 2.1, a comparison between the human and the cobots is presented. The main advantages and disadvantages of both are summed on this table.

<table>
<thead>
<tr>
<th>Human</th>
<th>Collaborative Robot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tireness, exhaustion</td>
<td>Tireless</td>
</tr>
<tr>
<td>Imprecise</td>
<td>High precision</td>
</tr>
<tr>
<td>Limit of speed</td>
<td>High speed</td>
</tr>
<tr>
<td>Free decision making</td>
<td>Defined decision making</td>
</tr>
<tr>
<td>Flexibility and easy adaption</td>
<td>Reprogramming, possible limitations</td>
</tr>
<tr>
<td>Common logic</td>
<td>Need of detailed task definition (programming)</td>
</tr>
<tr>
<td>Vision</td>
<td>Need of sensors and external devices to “see”</td>
</tr>
<tr>
<td>Use of all senses</td>
<td>Does not taste, smell, touch, hear, see</td>
</tr>
</tbody>
</table>

Table 2.1: Human Vs Cobot

2.6 Chapter Summary

In the current chapter, it was defined what a collaborative robot is. The history of them, starting as Intelligent Assist Devices and ending up to their present form. Moreover, the different types of collaborative robots were mentioned, as well as the 4 Industrial Revolutions. Emphasis was given to Industry 4.0 or 4th Industrial Revolution and the importance of collaborative robots on it. Furthermore, the advantages of the collaborative robots were presented, and a comparison between the the human factor and the cobot was made.

In chapter 3, that follows, the project is described in detail, including all the equipment and devices used. The programming logic and working flow is explained thoroughly.
References


Chapter 3
Project Description

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3.1 Introduction

In the current chapter all the different elements and devices that compose the project will be described in detail. There are electrical and neumatic devices that are used in order to perform the desired work. Moreover, there are devices that ensure the safety of the people and the process. Furthermore, the programming logic and sequence is elaborated step by step.

3.2 Project Description

The Auto Corrugate Loader (ACL) has the objective to remove the bundles from the pallet and to supply the magazine of the Automatic Case Packer (ACP) with the cases in the right position and without the straps, all of that in an automated way in order to eliminate physical effort from the operators, improving the ergonomy of the work and allowing attention to other activities of the operation.

The ACL is composed by a collaborative robot and a Workstation (WS). The collaborative robot (Figure 3.1) has the objective to check the orientation of the bundles of boxes and moving them from the pallet to the WS and afterwards to the magazine of the Automatic Case Packer (Figure 3.2), while the WS (Figure 3.3) is responsible for cutting the straps from the bundles and remove them.

Figure 3.1: Collaborative Robot
3.2.1 Collaborative Robot

The collaborative robot consists of a robotic arm with an end effector that has the shape of a gripper (also called EOAT – End of Arm Tool) in the end. The robotic arm is divided in 6 different joints, the base (A), the shoulder (B), the elbow (C) and the wrists 1 (D), 2 (E) and 3 (F) as seen in Figure 3.4. The gripper has two vacuum cups for repositioning the bundles and four “fingers” with “inflatable bladders” attached to them, which are used to effectively grab and transport the bundles (Figure 3.5).
The Cobot also consists of a Touchscreen Panel (TP) or teach pendant which allows the interaction between the operator and the robot (Figure 3.6).

The Gripper also has three sensors, two photoelectrical (digital), one ultrasonic (analogic) and one QR reader, which are shown at Figure 3.7 and Figure 3.8, respectively, and are responsible for assisting the robot in several parts of the program logical sequence.
3.2.2 Workstation

The Offline Workstation (OWS) is responsible for cutting the straps of the bundles, collecting them and removing them from the feature.
Figure 3.9 shows the two wedges which move sideways in order to tension the straps, and in the middle, there are two blades responsible for cutting the tensioned straps. The Figure 3.9 also indicates the ejectors, which are responsible for sucking the straps using vacuum through hoses which take them to a box where they are deposited (Figure 3.10)

![Figure 3.9: Workstation’s Wedges, Blades and Ejectors](image)

**Figure 3.9**: Workstation’s Wedges, Blades and Ejectors

![Figure 3.10: Staps Rubbish Bin](image)

**Figure 3.10**: Staps Rubbish Bin
The workstation also consists of 2 plates pushed by pistons which center the position of the bundle. The lateral plate which is moved by one piston (Figure 3.11) and the front plate, which is located on the strap cutter and is moved by 2 pistons (Figure 3.12). The strap cutter, in turn, is the element which contains the wedges and the blades.

Figure 3.11: Lateral Correction Plate
3.2.3 Safety Laser Scanner

The ACL has two devices called safety laser scanners (S1 and S2) which detect the entry of something or someone in the ACL area. These sensors work like a light curtain.

The purpose of the Safety Laser Scanner is:
1. To ensure the operator’s safety during the tasks in the ACL
2. To ensure the correct blockade of dangerous energy during the tasks in the ACL

**Figure 3.13** and **Figure 3.14** below show that the ACL is protected by acrylic guards and has two entrances for the operators to access the pallet and the magazine. The safety laser scanners are installed in these entrances to ensure that the robot interrupts instantaneously its operation and stops in case an operator enters its area of work, for safety purposes. The delimited area in the figure is the area protected by the Laser Scanner and, if transposed, the stop will be triggered.

**Figure 3.13:** Laser Scanner S1

**Figure 3.14:** Laser Scanner S2
When the safety laser scanner detects something or someone transposing its light curtain the red LED will be activated (Figure 3.15), otherwise the green LED will be on (Figure 3.16).

Figure 3.15: Laser Scanner Triggered

When the Laser Scanner Safeguard light curtain detects something as described above, the operation of the robot will be paused instantaneously. In this case, the robot can be activated by pressing the reset button indicated on Figure 3.17.

It is important to notice the reset will only work if the Laser Scanner Safeguard is clear, or in other words, if both Laser Scanners LED are green.

Figure 3.17: Panel Button Station (PBS)
3.2.4 Ultrasonic Analog Sensor

It is mounted on the gripper of the cobot. This sensor operates with ultrasonic rays and is used to detect the distance between the gripper and the bundle. The robotic arm is moving above every bundle, lowering its height every time a cycle has ended. Its voltage values, work as inputs to the programic logic in order to control the movements of the cobot.

3.2.5 QR Code Reader

It is also mounted on the gripper of the cobot. This reader is used to detect the QR code of the boxes. With the reader activated, the gripper is performing a search towards the two borders of the box. If the QR code is detected in the first border of the box it gets the value 1, otherwise if it is detected in the second border of the box it gets the value 2. Through that process the program understands if an 180° rotation is necessary or not before dropping the bundle to the Workstation.

3.2.6 Digital Sensors

There are two mounted on the gripper and one is located in the automatic case packer. The first two are used to detect the border of the bundle and correct the orientation of the gripper, before accessing the bundle to grab it. The other sensor is located on the automatic case packer and when is not activated, triggers the program to aliment boxes.

3.2.7 Safety System

The ACL safety system has electrical and pneumatic energy blocking devices in order to ensure the operators’ integrity. However, even with the automatic blockade, every time someone accesses the feature has to lock the mechanical latch of the reset button, as illustrated in Figure 3.18. This is necessary because once entered inside the ACL area, the Laser Scanner Safeguard will be activated, but if someone that is outside presses the reset button, the robot will start to move again, and it can cause an incident with the operator inside the ACL. In order to prevent this from happening, the use of the padlock during every intervention inside the limits of the ACL guards is mandatory.
Specifically, for the Offline Workstation area and the Strap Cutter, which has blades activated by compressed air, there are two energy blocking devices: the CAT IV valve and the Air Dump (Figure 3.19). The CAT IV valve blocks the air automatically every time someone crosses the Safety Laser Scanner. The Air Dump, on the other hand, has to be activated manually and locked up with the padlock.

### 3.3 Logic and Program Structure

The programming of the cobot is performed in the PolyScope environment at its teach tendant. The production line is fabricating around 25 different product references. In order to handle effectively this high variation, by writing a generic code that can apply to all the product references, the programming logic is based on the following principles:

- The different values of every product reference are defined in a table called recipe. Every product reference has its own recipe and is stored in the processor of the production line. When the fabricated product reference changes, the processor of the cobot reads the active recipe from the processor of the line and adjusts its values. *Example*: height, width, length, weight of the box.

- In order to facilitate the programming logic, installation variables are used. These variables are fixed coordinates of the Workstation origin, the Pallet origin and the Automatic Case Packer origin in function of the cobot’s origin (Table 3.1).
**Example:** pallet origin position on the axis X.

<table>
<thead>
<tr>
<th>With Installation Variables</th>
<th>Without Installation Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>➢ Pallet-Origin_X = -0.5545</td>
<td>Box_Center = p [-0.5545 + Bundle_Width, 0.8456 - Bundle_Length, 1.2336 - Bundle_Height, 0, 0, 0]</td>
</tr>
<tr>
<td>➢ Pallet-Origin_Y = 0.8456</td>
<td></td>
</tr>
<tr>
<td>➢ Pallet-Origin_Z = 1.2336</td>
<td></td>
</tr>
<tr>
<td>Box_Center = p [Pallet-Origin_X + Bundle_Width, Pallet-Origin_Y - Bundle_Length, Pallet-Origin_Z + Bundle_Height, 0, 0, 0]</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.1: Installation Variables**

➢ Important points of the code, that facilitate the programming, are defined as Program Variables. These points change their value according to the loaded recipe.

**Table 3.2: Program Variables**

<table>
<thead>
<tr>
<th>With Program Variables</th>
<th>Without Program Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box_Center = p [Pallet-Origin_X + Bundle_Width, Pallet-Origin_Y - Bundle_Length, Pallet-Origin_Z + Bundle_Height, 0, 0, 0]</td>
<td>Move L p [Pallet-Origin_X + Bundle_Width, Pallet-Origin_Y - Bundle_Length, Pallet-Origin_Z + Bundle_Height, 0, 0, 0]</td>
</tr>
<tr>
<td>Move L</td>
<td></td>
</tr>
<tr>
<td>Box_Center</td>
<td></td>
</tr>
</tbody>
</table>

**3.3.1 Tool Central Point**

The tool center point (TCP) is defined by the exact translational and rotational difference between the robot flange frame and the tip of the end effector.

In our case we have defined 4 different tools or TCPs, which are the following:

i. TCP 1: Analog Detector.

ii. TCP 2: QR Code Reader.

iii. TCP 3: Vacuum Caps.

iv. TCP 4: Digital Sensors.

The programming logic of the Cobot is structured in Subprograms as follows:

- Before Start Sequence.
- Step 0: Definition Type of Pallet.
• Step 1: Pallet Height Test.
• Step 2: Reading Qr / Datamatrix Code.
• Step 3: Separation with Vacuum Cups.
• Step 4: Gripper’s Correction & Bundle’s Capture.
• Step 5: Route from Pallet to Workstation.
• Step 6: Placement in WorkStation.
• Step 7: Straps Removal and Rotation of the Arm.
• Step 8: Capture from WorkStation and Placement to Case Packer.
• Step 9: Return to Pallet

* When starting the program, the Before Start sequence is executed first, then we have a program variable called Step that starts in Step 0 (Definition Type of Palet). Depending on the value of this variable, the Software executes the corresponding step. The variable step is increased by 1 when completing the corresponding step and when completing Step 9 it returns to 1.

3.3.2 Before Start Sequence

A Before Start Sequence is executed before the initiation of the program. If the program is paused, it will continue from the point where it was paused, but in case it is interrupted it will begin from the before start. If the programming sequence is not interrupted or paused the Before Start Sequence will be executed only once in the beginning.

In the Before Start Sequence the following processes are included:

- Set of Outputs to 0.
- Search and load recipe (reference variables).
- Initial assignment of the program variables.
- Home Position (program start).
- Sequence of Home Position (“safe” route using different waypoints to return to the Home position avoiding collisions).
3.3.3 Step 0: Pallet Type Definition

In this part of the code, the cobot reads the type of pallet processed and its mosaic from the recipe, in order to determine the program routine that it will execute. This step is outside the Before Start sequence and is executed only the first time we run the program (Figure 3.20).

![Pallet Type Definition Diagram]

**Figure 3.20: Pallet Type Definition**

3.3.4 Step 1: Detect Pallet Height

This step is performed to detect the height of the pallet, as well as to find its starting position. In the beginning, the TCP 1 (analog detector) is set. The gripper starts from the Home Position and from a certain height Z. Then, is moving above the center of every bundle following a predefined sequence. The bundles of each layer will be alimented in a certain order, so it starts from the center of bundle 1, goes to the center of bundle 2 maintaining its height Z, then to the center of bundle 3, then to the center of bundle 4 and back to the center of bundle 1, but this time reducing its height by Z minus 5 cm. The program exits this loop and moves to step 2, when the analog detector has a value less than 5 V, this means that has detected a bundle (Figure 3.21, Figure 3.22). If the analog detector reaches a value of 3 V, it means that no bundles have left, and the pallet is empty. In this case an automatic message pops up in the teach pendant of the cobot informing the operator and requesting him to replace the pallet.
3.3.5 Step 2: QR Code Reader

This step is performed to detect the orientation of the bundle. The bundles are oriented $180^0$ alternately in every layer of the pallet (Figure 3.23). Initially, the TCP 2 (QR Code Reader) is set. When the analog detector has detected the height of the pallet, the wrist 3 of the gripper turns $90^0$ and the QR reader is activated (Figure
The gripper performs an H movement from the center of the box in order to detect the position of the QR code. If the QR code is detected on the first border of the box the variable $QR\ Position$ gets the value 1, otherwise if the QR code is detected on the second border of the box the variable $QR\ Position$ gets the value 2 (Figure 3.25). The position of the QR code is important in order to place the bundle on the right orientation into the Workstation.
3.3.6 Step 3: Vacuum Cups Separation

This step is performed in order to separate the bundles that are attached to each other and create the necessary space for the gripper to access and grab them. Initially, the TCP 3 (Vacuum Cups) is set. The gripper lowers until the analog detector reaches a value of 0.7 V. At this point the vacuum cups are in contact with the box. The vacuum cups are activated, the payload changes to the weight of the gripper plus the weight of the bundle and the new center of mass is set. The bundle is slightly risen and separated from the other, in order to create the beforementioned necessary space (Figure 3.26, Figure 3.27).

![Figure 3.26: Vacuum Cups Separation](image1)

![Figure 3.27: Separated Bundles](image2)
3.3.7 Step 4: Gripper’s Correction & Bundle’s Capture

This step is performed in order to grab successfully the bundle of boxes. The orientation of the bundle in 90% of the cases it is not the desired one. For this reason, it is very important to correct the orientation of the gripper before accessing the bundle to grab it. Initially, the TCP 4 (Digital Sensors) is set. The gripper is positioned above the bundle with the two sensors detecting its surface. The gripper starts moving towards the border of the bundle until the first sensor does not detect. Then, the gripper moves to the center of the bundle. Subsequently, the gripper starts moving towards the other border of the bundle. When the first sensor stops detecting, the gripper performs angular corrections in one direction or another until both sensors stop detecting. At this point the gripper access the bundle.

![Gripper’s Correction](image)

**Figure: 3.28** Gripper’s Correction

3.3.8 Step 5: Route from Pallet to Workstation

This step is performed in order to move the bundle from the pallet to the Workstation. The waypoints followed are fixed, regardless of bundle’s position. The same sequence is followed in order to simplify the process.

3.3.9 Step 6: Placement in Workstation

During this step the bundle is placed on the Workstation with the correct orientation. During this sequence the TCP 4 stays active. The cobot before dropping the bundle makes an $180^\circ$ rotation, if needed, which depends on the position of the QR
code. The correct orientation of the bundle into the Workstation is very important, otherwise the Workstation will not be able to cut the straps either aspire them.

3.3.10 Step 7: Straps Removal and Rotation of the Arm.

First of all, the lateral and front correction plates are activated in order to align any disalignment of the bundle. Then, the two straps of the bundle are cut by the blades and removed by the ejectors. In parallel, the base of the cobot is performing a 360° rotation. This rotation is essential in order to give the arm the reach needed for the next step. The cutting and removal process of the straps is presented on Table 3.3.

<table>
<thead>
<tr>
<th>Output State</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejectors Up</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ejectors</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Lateral Frame</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Front Frame</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Wedges</td>
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<td>0</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>Blades</td>
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<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ejectors Down</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.3: Digital Outputs State

3.3.11 Step 8: Capture from WorkStation and Placement to Case Packer

This step is the same for all the bundle positions and orientations and is defined as a subroutine of the program. During this sequence the TCP 4 stays active. The gripper remains above the bundle on standby mode, until the automatic case packer “asks” for more boxes. This happens through a digital sensor installed. When the sensor does not detect any box, sends a signal to the program to continue its sequence. When the signal is triggered the gripper lowers on the Z axis until the springs are compressed 20mm. Then, the arm approaches the automatic case packer, the inflatable bladders deactivate, and the springs push the boxes from the gripper. The arm lower 2 cm and exits the automatic case packer in a secure way.

3.3.12 Step 9: Return to Pallet

Finally, the robotic arm follows a standard route and returns to the pallet. The step is set again to 1 and the process continues with the next bundle.
3.4 Chapter Summary

Initially, the project is described. The collaborative robot, the workstation, the different devices installed on the gripper and the safety scanners are described in detail. Subsequently, the program logic is analysed and how the different devices used, affect the process.
Conclusions

Scope of the current degree project was the description of the installation of a collaborative robot in the production line. It is a real case project and need of a production line. The project was developed according to the project management theory.

Although the project has not closed yet, since it is at its ultimate phase, couple of conclusions can be extracted.

The project has 2 months delay according to the initial timetable. The reasons are various:

**Resources Change:** the initial core team of the project was modified during the implementation of the project. A new member was added to the core team, without the necessary integration training of the standards and processes of the company, provoking in some cases confusion. Another member of the team, dedicated to the program logic development was placed to another position for 3 months, removed practically from the project. The person who substituted him was not previously trained to programming, causing significant delays until he reached a certain level of understanding and knowledge. One month before the completion the project manager of the project left the company, leaving the team without its organizer. Furthermore, due to wrong planning one month during the summer the project was paused, because there were no personnel available.

**Project’s Requirements Definition:** as beforementioned the initial development of the project was performed in another production plant and bought by our plant. Although, the scope is the same in both cases, the alimentation process of the boxes from the pallet to the Automatic Case Packer is quietly different. The Automatic Case Packer of the other plant is different. It is a new machine with an inclined case erector. This inclination prevents the fall of the boxes when the case packer is activated. In our case, that was a significant problem, since the erector can not beinclined.

Another issue was the weight of the gripper. The boxes we are using are bigger and heavier, making it impossible to lift them, since the maximum lifting weight of the cobot is 10 kg. The problem was solved by reducing the weight of the gripper.
Another, issued faced, was cutting the straps. Every bundle consists of 17 boxes, while in the other plant every bundle contains 23 boxes. This difference of boxes is translated to the height of every bundle. Since there are 2 wedges and blades in different heights, the superior one was not able to engage the strap of the bundle. After modifications to the shape of the wedges, the blades and the workstation the cutting was achieved.

In addition, the alimentation pace of our automatic case packer is 4 times faster than the other. That means, that an improved, faster programmic sequence had to be developed to achieve the required time cycles.

**Cost Incrementation:** During the installation of the project were performed around 22 improvements or modifications of the initial equipment. These modifications are divided into 3 categories, mechanical, electrical and pneumatic. The total cost of these modifications was around 19.000 €. This corresponds to 23% cost incrementation of the initial budget. However, in the initial budget an additional budget of 20.000 € for improvements had been included. The main reason that these modifications were necessary, was the insufficient project’s requirements definition. As beforementioned, the requirements in our plant are different, comparing to the other plant that was first installed the project. These differencations were not analysed sufficiently, causing problems during the installation phase. In addition, since there was a limit of additional money that could be used, all the improvements were made after analysis and tests in order to guarantee their success. In the other hand, these tests and analysis led to schedule delays.

**Future Work**

Through the implementation of the project, many experiences were gained and lessons were captured. In this paragraph a couple of future propositions for improvements of the process will be presented. Since the implementation of these improvements did not constitute stoppers of the process, and would cause extra time delays and cost incrementation, were decided not to be made. However, these modifications can increase the process integrity and reliability, decrease the time cycles and wide the capabilities and the application of the process.

**Ultrasonic Sensor:** the existing ultrasonic sensor, used to detect the height of the palet, and select the appropriate bundle position in order to start the cycle. The
existing sensor is a SICK UM30-2121113 with maximum operating range 600 mm and can be substituted with the SICK UM30-2131118, a similar sensor, but with maximum operating range of 2.000 mm. Through that change the cycle time of the process will be reduced significantly since, the gripper will have to make only an initial search above the palet and directly move towards the bundle position that will be processed.

**QR Code Reader:** In order to find the bundle’s orientation a QR code reader is used. The reader is mounted on the gripper of the cobot. The proposed solution suggests the removal of the reader from the gripper and use of a high-resolution camera below the Workstation. When the arm will bring the bundle above the Workstation, the camera will be activated and read the position of the QR code. According to the position read from the camera, the arm will place the bundle with the right orientation to the Workstation. The new system, will decrease the weight of the gripper around 350 grams, enabling to process heavier references. Moreover, the presence of a camera below the Workstation, will ensure that there will be no boxes left on the Workstation.

**Cutting System:** The existing system of engaging and cutting the straps of the bundles consists of 2 wedges in different heights, an inferior and a superior, which contain 2 blades. The success of the cut depends on the position of the 2 straps as well as of the bundle’s height. The proposed solution, consists of one mechanism in the center of the bundle, with 2 united wedges carrying independent blades. This system will eliminate the bundle’s height restriction, as well as the position of the straps.

**Case Erector:** The original system included 2 retainers that secure the boxes from falling back, due to the force that the boxes undergo when the vacuum sanctions of the automatic case former are activated. In the original system these retainers were positioned by the operator. These retainers were removed since the robot cannot place them. In order to absorb this force, the boxes are placed inclined in the automatic case former. However, this solution can not guarantee the absolute success of the process. The proposed solution is to design and install rails on the automatic case former where the retainers will be positioned. When the arm approaches the case erector, the retainers will move back. After the area is clear from the arm, the retainers will move forward to secure the falling of the boxes.