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Developing an assembly line: the Ingersoll Rand Case

MASTER'S DEGREE THESIS IN
MANAGEMENT ENGINEERING
INGEGNERIA GESTIONALE

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Abstract

This master thesis reports a real case study carried out in the Italian plant of Ingersoll Rand, a global market leader operating in the industrial sector.

The project was launched by the company to satisfy the need for the implementation of a new assembly line. Indeed, following the shutdown of a plant in the Czech Republic, the Italian plant of the company was requested to sustain the entire Czech production of rotary compressors. Therefore, the project work consisted of the creation of a dedicated assembly line exploiting Lean thinking. In particular, the project followed the A3 steps, the problem-solving tool developed by Toyota.

The analysis of the problem started with a pilot test of the assembly. The pilot test highlighted that a huge amount of time was wasted during the assembly. Therefore, targets were set together with the stakeholders towards the reduction of wasted time. The Ishikawa diagram and the 5 Whys Method allowed the identification and analysis of the root causes. Some countermeasures were developed to remove those root causes and to reach the targets. Lastly, a plan of implementation of actions was developed. The implementation of the complete assembly line is not included in this master thesis, since it will be concluded by 2023. Therefore, this master thesis does not contain the direct monitoring of results. However, the impact of each countermeasure was estimated. Estimated results show that the assembly line and proposed countermeasures are expected to successfully satisfy the must-have targets and some of the nice-to-have ones.

Abstract in italiano

Questa tesi di laurea magistrale riporta un vero caso di studio realizzato nello stabilimento italiano di Ingersoll Rand, leader mondiale nel settore industriale.

Il progetto è stato lanciato dall'azienda per soddisfare l'esigenza di realizzare una nuova linea di assemblaggio. Infatti, in seguito alla chiusura dell'impianto in Repubblica Ceca, l'impianto italiano è stato incaricato di sostenere l'intera produzione ceca di compressori rotativi. Pertanto, il progetto si propone di creare una linea di assemblaggio dedicata sfruttando la filosofia Lean. In particolare, il progetto ha seguito le fasi A3, lo strumento di problem-solving sviluppato da Toyota.

L'analisi del problema è iniziata con un test pilota dell'assemblaggio. Il test pilota ha evidenziato che un'enorme quantità di tempo è stata sprecata durante l'assemblaggio. Pertanto, sono stati fissati gli obiettivi insieme agli stakeholders per la riduzione del tempo perso. Il diagramma di Ishikawa e il metodo delle 5 Whys hanno permesso l'identificazione e l'analisi delle cause primarie. Alcune contromisure sono state proposte per eliminare tali cause e per raggiungere gli obiettivi. Infine, è stato sviluppato un piano di attuazione delle azioni. L'implementazione della linea di assemblaggio completa non è inclusa in questa tesi di laurea, poiché sarà conclusa entro il 2023. Pertanto, questa tesi di laurea non contiene il monitoraggio diretto dei risultati. Tuttavia, l'impatto di ogni contromisura è stato stimato. I risultati stimati mostrano che la linea di assemblaggio e le contromisure proposte saranno in grado di soddisfare con successo gli obiettivi must-have e alcuni di quelli nice-to-have.

This document does not contain classified information

Contents

1 Executive Summary

1.1. Company Overview

Ingersoll Rand is a multinational organization and a global market leader in the industrial sector. It employs over 16,000 people in more than 60 countries around the world and sells its products to companies operating in various sectors, such as Aerospace, the Chemical, Electronics, Environmental, and even Food and Beverage. Ingersoll Rand Italia is located in Vignate (Lombardy), where the project work of this master thesis took place. The Vignate plant extends for 7400 square meters and employs around 300 workers every day.

1.2. The problem

Every year the plant produces around 200 compressors and ships them to businesses worldwide. Ingersoll Rand in Vignate is specialized in centrifugal compressors, a very customized product and which the company almost entirely produces inside the plant. Starting from 2021, Ingersoll Rand Italia is requested to produce a new type of compressor, the rotary one, after the shutdown of the dedicated plant in the Czech Republic. The Italian plant faces the production of rotary compressors only around 1.2 times per year. In those extraordinary cases, a task force is built, and the rotary compressors are assembled employing days of work. Ingersoll Rand Italia is now requested to reach the target of 60 rotary compressors produced per year.

Comparing the production rhythm of the Czech plant, which employed 4 hours per station, to the 3.5-times slower rhythm of the plant in Vignate, together with the 35-times bigger expected output, it is clear how an improvement action is needed. Therefore, the company launched a Lean project aiming to define and optimize an assembly line dedicated to the new product.

1.3. The goal

After the problem was analyzed, desired targets were set together with the stakeholders. The objective of the project was to optimize and customize the assembly line dedicated to rotary compressors starting from the Czech model: 5 assembly stations.

The main goal is to reduce the time wasted to reach the target of 7.5 hours per station. This means that potentially a unit is assembled in one day. At the same time, the stabilization of the line is required. This is expected to be reached through the reduction of reworks and the introduction of a method to monitor the performance of the upcoming assembly line using the Lean tool SQDPI board.

Furthermore, an additional point could contribute to further satisfying the stakeholders: the creation of clear work instructions and of an efficient layout.

1.4. The Methodology

This project work was analyzed by exploiting Lean thinking principles.

The term Lean was first used to describe the Toyota Production System. TPS was developed in the Japanese plant of Toyota during the 1950s and 1960s and it pursues the elimination of all waste with the objective of satisfying customers' orders quickly and efficiently.

In 1996 Womack and Jones proposed a five steps approach to guide managers and organizations through a lean transformation, known as the 5 Lean Principles:

1. Identify the Value
2. Map the Value Stream
3. Create a Flow
4. Establish Pull
5. Seek Perfection

Throughout the years, many lean tools were developed. One of these is the problem-solving A3, an 8 steps approach to identify the problem, analyze the current situation, set targets, identify root causes, propose countermeasures, define a plan of implementation, monitor the results and propose follow-up actions.

The A3 is the tool selected to guide the execution of this project work.

1.5. The Analysis

On the 21st of April, a pilot test of the assembly of a rotary compressor was performed. Observing the operator throughout the whole assembly of the unit allowed the mapping of all the performed activities, assembled components, used tools, and it was crucial for discovering issues and gathering suggestions from the operator that could help in easing the whole assembly and avoiding wasted time. The results of the pilot test showed that the stations' durations were very different one from the other and were higher than the target set to 7.5 hours. The slowest station lasted 19.5 hours and the fastest one 9 hours. The main issue is the huge amount of time that is wasted during the assembly activities.

Using the Ishikawa diagram and the 5 Whys method, 11 root causes were identified:

- Unexperienced workers in the People class
- Unclear procedure and drawings and language in the Process class
- Messy cart, not provided tools and inefficient layout in Equipment class
- Wrong screws as regards Materials
- Dependence on Russia and Shanghai in the Environment class
- Not updated management system, pieces not in BOM and pieces not reserved as regard Management.

Therefore, 7 countermeasures were developed to remove those root causes:

- Training and Learning by Doing: this countermeasure consists in defining a training plan to assemble a dedicated unit under the supervision, guidance and help of the operator of the pilot test. In this way, they will gain the know-how, and this will reduce wasted time.
- Customized Procedure: the objective was to provide clear and easy-to-understand work instruction. After the translation from the Czech language to the Italian one, the procedure underwent the selection of useful and clear technical drawings and a revision of the order of the operations. The SQIDP board was also prepared in this phase.
- Adjusting Line Layout: the area was cleaned and the distribution of the stations and of the working areas was defined. A safe and easy manual handling system was selected.

- Wall of Tools: using the list of tools filled during the mapping activity of the pilot test, a wall of required tools was developed for each station. This is expected to reduce the wasted time and the movement outside the operator's area.
- Clean Cart to keep the workspace tidy and free from unnecessary things.
- Self-tapping Screws: the long-term solution consists in substituting the AS-IS screws with self-tapping ones to avoid screw breakages during the assembly. A short-term fixing solution was also provided: the use of screwdrivers.
- Updating Management System: using the list of components mapped during the pilot test, the management system was updated to avoid missing pieces.

1.6. The Results

The implementation of an assembly line from zero takes time to be completed and that's why it is planned to be concluded in 2023.

Furthermore, after the pilot test, no other rotary compressors were planned to be assembled before the month of July. Therefore, this master thesis does not include the direct monitoring of results. However, an estimation of the impact of each countermeasure is given based on the data collected during the pilot test and performing, when possible, simulations.

The *Wall of Tools* collects all the tools that were used during the pilot test; therefore, it is reasonable to expect that the time spent looking for tools will be halved and a maximum of 2 movements will be required. The *Clean Cart* will guarantee a tidy and clean workspace.

The *Customized Procedure* together with the *Training & Learning By Doing* is estimated to reduce the understanding time by 84%. The new procedure is expected to reduce by 71% the duration of reworks. The Self-tapping Screws will be implemented in 2023. The fixing solution suggests using screwdrivers which were tested and reduced by 86% the tapping time. It is impossible to act on the Environment causes such as the Ukrainian and Chinese situations. However, the *Updating* of the management system is expected to avoid the missing pieces that are due to causes included in the scope of the project (errors in the BOM and the system).

Lastly, the *Customized Procedure*, the use of *Screwdrivers* and *Updating Management System* together are expected to ensure the satisfaction of the target of 7.5 hours per station.

2 Introduction

2.1. Company Overview

This master thesis reports the project work that has been carried out through a real case study in the Italian plant of the multinational company Ingersoll Rand. The real case study consisted in performing a continuous improvement project aimed at defining and optimizing the assembly line for a newly introduced product in the Italian plant of the company.

Ingersoll Rand is a global market leader operating in the industrial sector. The company offers a wide range of innovative technologies for air, fluid, energy, and medical sectors to increase industrial productivity and efficiency. Ingersoll Rand provides products ranging from complete air compressor systems, tools, ARO pumps, material handling systems, and more to businesses around the world (B2B).

Figure 1: Ingersoll Rand LOGO

In 1872 Simon Ingersoll patented his steam-powered rock drill giving birth to Ingersoll Rock Drill Company. Then, in 1890, the company introduced the world's first direct-connected, electric motor-driven compressor, officially initiating the successful future of expansion of Ingersoll Rand.

Throughout the decades of activity, Ingersoll Rand enriched the market with innovative products, introducing:

- the Imperial X-Type portable compressor available with steam or electric drive in 1900,
- the first oil-free centrifugal compressor in 1912,
- the compact and efficient legendary Type-30 compressor in 1929,
- the first gas turbine-driven pipeline compressor in 1949,
- the first two-stage oil-free rotary industrial compressor module in 1953,
- the Centac centrifugal product line in 1953,

- Nirvana, the first variable speed rotary screw compressor in 2002.

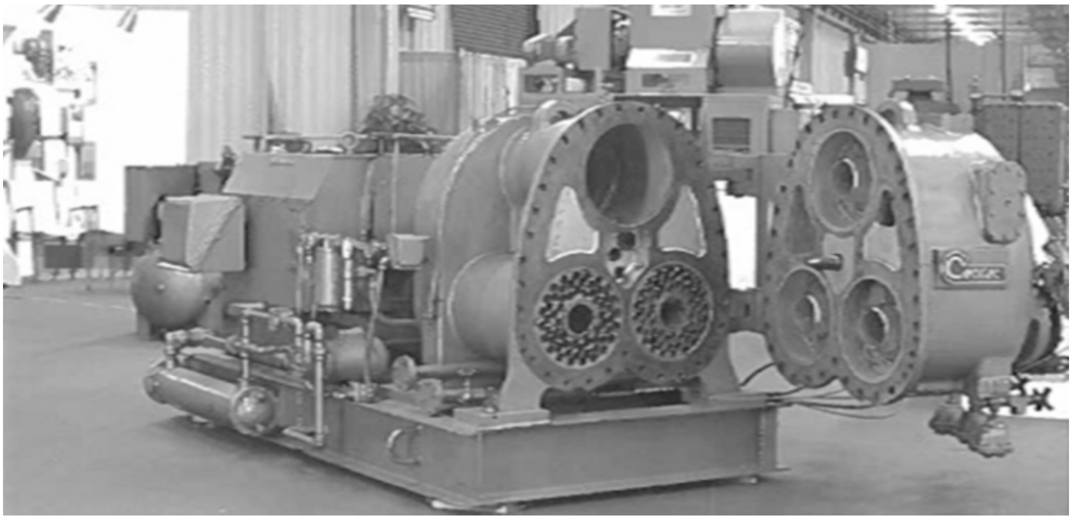


Figure 2: Centac 1953

In 2020 Ingersoll Rand merged with Gardner Denver gaining a combined history of over 300 years and a shared commitment to operational excellence, innovation and quality.
Today Ingersoll Rand employs over 16,000 people in more than 60 countries around the world and gained 5.15 billion USD of Revenues in 2021 selling its products to companies ranging from Aerospace to Chemicals, Electronics, and Environmental sectors and even Food and Beverage industries.
Ingersoll Rand Italia is located in Vignate (Lombardy), where the project work of this master thesis took place.
The Vignate plant extends for 7400 square meters and employs around 300 workers every day. They are employed into 3 separate business societies:

- Ingersoll Rand Manufacturing Italiana Srl which employs around 160 workers in Operations related activities.
- Ingersoll Rand Italia Srl which is dedicated to Sales and After sales services.
- Elmo Rietschle, which is based in the Vignate plant but has no link to Ingersoll Rand company and activities.

Every year the plant produces around 200 compressors and ships them to businesses worldwide. Ingersoll Rand in Vignate is specialized in centrifugal compressors, which the company almost entirely produces inside the plant.

The Vignate product portfolio consists of highly customized centrifugal compressors of the following types:

- CENTAC, the top one product for the Vignate plant.
- TA
- NX

Starting from 2021, Ingersoll Rand in Vignate is requested to produce a new type of compressor, the rotary one. Being the plant completely devoted to centrifugal compressors, the company launched a Lean project aiming to define and optimize an assembly line dedicated to the new product.

2.2. Project Methodology

As already stated, this project work aims to exploit Lean Thinking capabilities and principles. Therefore, a presentation of the methodology used throughout the project with a focus on Lean Thinking Theory and Principles follows.

Lean Thinking refers to a way of thinking and taking business decisions where Lean indicates an approach to continuously improve business processes.

The term Lean was first used in 1988 by a MIT researcher, John Krafcik, who used it referring to the Toyota Production System (TPS). However, the term was made popular by the book *The Machine That Changed The World* (Womack et al. 1990), where it is described as a process that "[…] compared to mass production it uses less of everything – half the human effort in the factory, half the manufacturing space, half the investment in tools, half the engineering hours to develop a new product in half the time.".

In *How did the publication of the book The Machine That Changed The World change management thinking? Exploring 25 years of lean literature* (2015), the authors perform a literature review on Lean articles over 25 years from 1987 to 2013 to study how the concept evolved over time "from a generic description of TPS to a particular type of organizational and management intervention focused on best practice and process improvement methodologies". Furthermore, the authors show how even in the absence of a clear definition of Lean, in 25 years Lean has become dominant as an approach to reduce variability and improve the flow. In addition, the authors demonstrate how Lean has spread even in its fields of application. From its birth in the automotive industry, today it influences many aspects of our life, and education and healthcare systems are just two examples (Samuel, et al., 2015).

Going back to the history of the term Lean, it was first used to describe the Toyota Production System. TPS was developed in the Japanese plant of Toyota during the 1950s and 1960s. TPS pursues the elimination of all waste to satisfy customers' orders quickly and efficiently. TPS can be represented as a house where the main two pillars are the concepts of Just-in-Time and Jidoka. The former consists in producing only "what is needed, when it is needed, and in the amount needed" or requested or pulled from the next step of the production process. This leads to the elimination of all forms of waste.

In Japanese wastes are called:

- Muda which indicates non-value-adding activities and is classified into transport, inventory, motion, waiting, overproduction, over-processing, and defects.
- Muri, or overburden of equipment and people, which can be avoided by assigning operators sufficient time to perform the required task.
- Mura, or irregularity and unevenness in the production process, which are to be identified and leveled.

The key elements to reach JIT are Continuous Flow, Takt Time and Pull System. These will be clarified later.

Jidoka is referred to as “automatization with a human touch” and consists in separating human tasks from machine tasks and safely stopping the machine whenever an abnormality occurs to prevent the production of any defective pieces.

The two pillars, JIT and Jidoka, stand on the base of the house which consists of the concepts of Heijunka, Standardized Work and Kaizen.

The first one, Heijunka, means production leveling. It consists in computing the average production volumes and maintaining them to ensure smooth production in all departments. It is crucial in allowing the production to react to demand changes and to utilize the available capacity in the best possible way. By implementing Heijunka, the production uses no more batches but is pulled by customer orders. In such a way, inventory level and related costs are reduced.

The second concept, Standardized Work, represents the best practice to perform a process in the most efficient way and maximize customer satisfaction. It consists in establishing a clear procedure of tasks an operator must follow in a production process. It is based on:

- The Takt Time, the rate at which pieces must be produced to meet customer demand. Therefore, it is defined as the ratio between the time available for production and the market demand. If the process exceeds the Takt Time, it results in scarcity of products while if it is faster, it results in overproduction. When Takt Time is respected, the whole process flows at the same pace producing the number of products demanded (Santos, et al., 2021).
- The work sequence of tasks that must be performed within takt time.
- The standard inventory and units in machines to let production flow smoothly.

Standardized work can be continuously improved through Kaizen.

Kaizen generates from the composition of two Japanese words, *kai* and *zen*, that stand for *change for the better* or *continuous improvement*. The continuous improvement consists in involving all the members of the organization in a never-ending process of further improvements.

A way Kaizen can be reached is through the implementation of a lean tool, called 5S. It is a methodology that results in a workspace that is clean, uncluttered and well-organized assuring reduction of waste and productivity optimization. The 5S method consists of:

- Seiri, or "Sort out": to separate needed tools, parts and instructions from unnecessary ones which must be removed from the workplace.
- Seiton, or "Set in order": to arrange and organize tools and parts in an easy-to-use way.
- Seiso, or "Shine": to clean the work area as a routine.
- Seiketsu, or "Standardize": to apply Seiri, Seiton and Seiso on a regular scheduled basis.
- Shitsuke, or "Sustain": to make 5S a way of life.

All the concepts building the TPS house allow reaching the goal of the highest quality, lowest cost and shortest lead time, which is represented as the roof of the house.

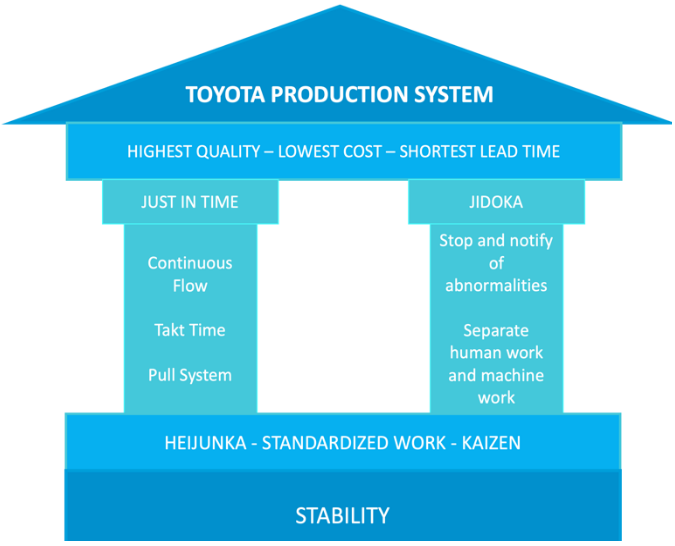


Figure 3: TPS House

In 1997, the Lean Enterprise Institute (LEI) was founded by management experts James P. Womack and Daniel T. Jones. The LEI is considered a community made of organizations, managers, team leaders and members that work every day together to achieve the goal of "making things better by advancing lean thinking and practice".

Womack and Jones in 1996 proposed a five steps approach to guide managers and organizations through a lean transformation. The steps are known as the 5 Lean Principles and enclose and explain the whole Lean Philosophy:

6. Identify the Value

   Value is what the customer is willing to pay. To sell products to the market you must discover what customers want, and what are their real needs. In order to do so interviews, surveys, and research can help you identify what customers want.

7. Map the Value Stream

   Using the identified value as a reference, you move on to identifying which activities contribute to the building of that value. Any activity that does not add any value to the customer is a waste. Among these, some may be non-value adding and unnecessary and must be eliminated, some others may be non-value adding but necessary and must be reduced to the minimum. In this way, you deliver to the customer exactly what they want at the minimum cost. Here, a useful tool is the Value Stream Map.

8. Create a Flow

   Now, you must ensure that production steps run smoothly without stoppages or delays. You need to identify what could cause interruptions in the process and remove it.

9. Establish Pull

   Lean promotes pull-based systems, where production is pulled, and triggered, only by real customer demand. Pieces are produced only when needed and in the quantities in which they are needed. Producing in advance and stocking pieces as inventory is a waste.

10. Seek Perfection

    Lean seeks for perfection in the sense that improvement is a never-ending process. Continuous improvement must become an intrinsic aspect of the organization. Every employee should be trained to and involved in improving and keeping improving the process every day in a never-ending horizon.

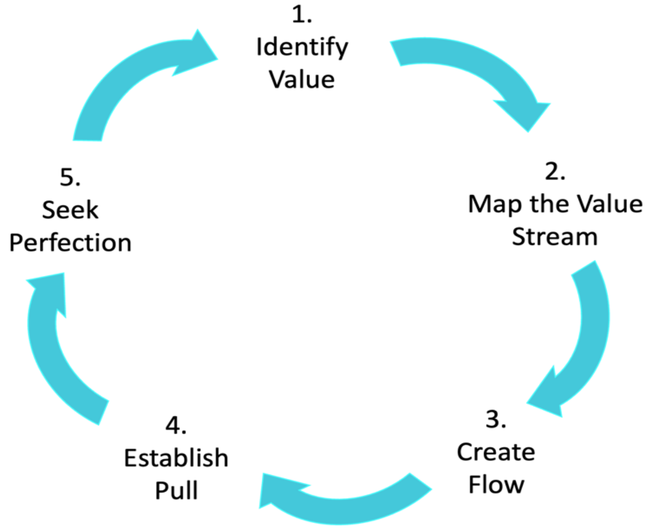


Figure 4: The 5 Lean Principles

In the following paragraphs, some lean tools useful to the scope of the project are briefly introduced.

THE A3 FRAMEWORK

The A3 Thinking was born in Toyota as an approach to continuous improvement. Toyota developed a simple tool, the A3 report for problem-solving, communication, knowledge-sharing and understanding the process and improving it on a continuous basis.

The A3 report is based on the Scientific method for Problem Solving, the Deming cycle, or PDCA (Plan, Do, Check, Act):

- Plan: phase in which the problem is evaluated and analyzed, corrective actions are decided, and targets are defined.
- Do: the selected corrective actions are implemented.
- Check: the implemented solutions and results are checked, and it is verified if targets are achieved.
- Act: this phase is crucial as if targets are not achieved, then the cycle must be repeated from the first stage to understand where the failure comes from. Otherwise, if the goals are achieved, the project is made definitive, standardized, and repeated in all the other processes.

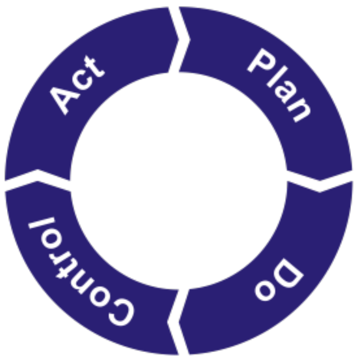


Figure 5: PDCA Cycle

The A3 report exists in three types:

- The proposal A3
- The status A3
- The problem-solving A3.

The proposal A3 report consists in a proposal made to the company. The issue tackled by the proposal might not be necessarily a problem that the company wants to address but it might be an opportunity. It consists of 7 steps: Background (Plan), Current state (Plan), Analysis of alternatives (Plan), Proposal (Plan), Plan Details (Plan), Unresolved issues (Plan), and Implementation schedule (Do, Check, Act).

The status A3 report is used to assess the project at various time instant during the project progress and to provide an end status. It consists of 4 steps: Background (Plan), Current State (Do), Results (Check), and Remaining issues and/or Follow-up actions (Act).

The problem-solving A3 report is defined as:

1. A tool for supporting problem setting and problem-solving.
2. A managerial approach to foster and develop a continuous improvement culture.

The problem-solving A3 is built on 7 key elements:

1. Logical thinking: it is not based on intuition; it is based on logical thinking and reasoned judgment on gathered data and evidence.
2. Objectivity: it is based on data as numbers avoid misunderstanding and do not lie.
3. Results and process: robustness of the process is crucial for robustness of results.
4. Synthesis, distillation, and visualization: only relevant information must be reported, and the use of graphs and visual elements is recommended.
5. Alignment: it must always be aligned to the strategy of the company.
6. Coherence within and consistency across
7. Systems viewpoint: even though it is analyzing a part of the system (for example, a production line), you must always think about it as a part of a bigger system.

The problem-solving A3 is made of blocks, or steps and is filled with graphs and significant images. Indeed, the A3 to be successful must be visual, quick, readable, and easily understandable at a first glance by everyone even without reading it.

It must involve employees, who are directly working in the process, but also managers who will have a simple tool to look at the state of the process.

The problem-solving A3 framework foresees 8 steps:

1. Problem Background (Plan)

   It answers the question "Why is it a problem?" and defines and describes the problem and its main features.

2. Problem Breakdown - Current Situation (Plan)

   It analyzes the current situation (AS-IS) gathered through observation of the work process and quantifying its elements.

3. Target (Plan)

   It defines the targets that are intended to be reached after the improvements. Targets must be SMART: specific, measurable, attainable, realistic and time-based.

4. Root Cause Analysis (Plan)

   It searches for and identifies the root cause of the problem. Some tools that are useful in this phase are: the Ishikawa Diagram and the 5 Whys Method.

5. Countermeasures Development (Do)

   It presents the selected countermeasures that allow to remove root cause, if possible, and to improve the process to reach targets.

6. Countermeasures Implementation (Do)

   A plan for the implementation of countermeasures is defined, including tasks to be performed, due dates and responsible roles. Here, the Gantt Chart is very useful.

7. Monitor Results & Control (Check)

   In this phase, results from the countermeasures are monitored and evaluated against the defined targets.

8. Standardize & Share Success (Act)
   It consists of solidifying the knowledge gathered till now and sharing it throughout the whole organization.

The A3 report can be combined with some other Lean tools, such as:

- the Ishikawa Diagram, used to perform the Root Cause Analysis. It is a way to represent the causes of a problem in a Fishbone graphical structure where the head of the fish indicates the problem under analysis and the bones indicate the causes grouped in classes such as machine, man, equipment, and material.

- the 5 Whys Method, also used in the Root Cause Analysis. It is a tool to reach the root cause of a problem. It consists in digging in the knowledge, further asking why questions until the root cause is discovered. The root cause is the one for which a further reason cannot be questioned.

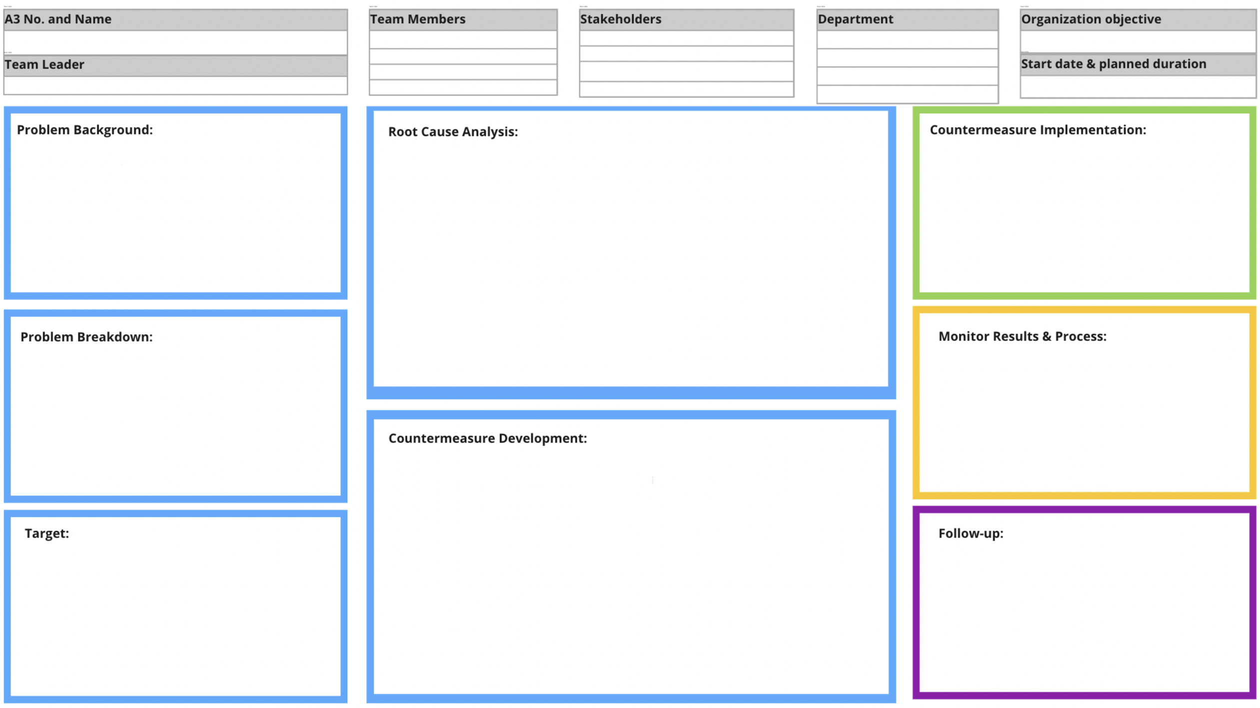


Figure 6: Example of the problem-solving A3 framework

- the Gantt Chart, typically used in the Countermeasures Implementation phase. It is a useful tool for representing activities and tasks displayed over time and highlighting roles and responsibilities for each of them.

VISUAL MANAGEMENT

Visual Management is a practical approach that consists in exploiting the immediacy and evidence that visual symbols and signs can give. Visual Management is a key tool in Lean and in representing the status of the process and is also crucial in the development of a successful and clear A3 framework.

Information is to be represented to satisfy some requirements:

- It must be relevant.
- It must be easily understandable at first sight and for doing so images are preferred. Fred R. Barnard stated “One picture is worth a thousand words” in 1927.
- It must be attractive and catchy: colors help in highlighting concepts.
- It must be updated in real time.

  Michael Ballé, a notable lean-novel author, in his book *The Leans Manager* states that “Visual Management is seeing together, so that we know together, so that we act together, from the operator to the CEO”.

KANBAN

Kanban is a Japanese word that means *sign* or *visual board* and initially indicated the pull scheduling system for lean manufacturing in TPS. It was in 2007 that it evolved into the *Kanban method*, a Lean workflow management method, applicable to everyday tasks and enhancing visibility of work, delivery speed, alignment between goals and execution and customer satisfaction. It includes six practices:

1. Visualize the workflow
2. Limit work in progress
3. Manage flow
4. Make process policies explicit
5. Implement feedback loops

6. Improve collaboratively.

The main tool to visualize the workflow is the Kanban board consisting of a whiteboard representing work phases as columns and on which sticky notes are moved from one stage to another.
Kanban also indicates the lean technique of using physical tags that allow the pull flow of materials. The goal of the kanban is to avoid overproduction which, as already stated, is a form of waste in Lean philosophy.
The kanban is a square card that contains the information necessary to produce, buy or handle components and materials in the production system:

Figure 7: Kanban Boxes in IR plant

1. The code of the component concerned
2. The supplier of that component
3. The customer who requests it
4. The time available for restoration
5. The quantity to be restored
6. The container to be used
7. Other personalized information

Kanban tags are placed on a container that contains a fixed amount of a component. Only after this material is consumed the tag is passed to the supplier who can restore the components consumed. The flow of materials in a kanban production is therefore defined as "pulled" because the production of a component is authorized only by actual consumption.
Kanban can be divided into two main types:

- The handling or transport kanban that are used to move components and materials towards a production process.

- The production Kanban which represents real production orders by which the upstream process is authorized to produce a certain component for a downstream process.

A HINT ON ASSEMBLY LINES

As mentioned before, this project work aims at defining an assembly line for a new product. Therefore, a hint on the assembly line is provided in the following paragraph.

Products can be manufactured by following two types of processes:

- Fabrication: when the product is made from zero starting from raw materials.
- Assembly: when components are put together to build the final product.

An assembly line is a manufacturing process consisting of a series of workstations in which parts are progressively added to semi-products as these products visit workstations following a pre-defined sequence of steps. Products may be moved by a conveyor belt or another transportation system from one station to another (Fortuni-Santos, et al., 2020).

Assembly lines are generally used for high volume and high repetitiveness production. Indeed, this type of manufacturing process guarantees the rationalization of material flows, low WIP (Work In Progress), limited space requirements and low cost for the workforce since labor training might be easy and no particular skills are needed. At the same time, assembly lines allow low flexibility, and suit repetitive work but require a long time to start new production and line balancing might be difficult.

Assembly lines are classified as:

- Single-model, when the line is dedicated to the assembly of one single type (model) of product.
- Multi-model, when different models of product are assembled in separate batches. It includes setup activities to change from one model to another.
- Mixed-model, when different models can be produced without any batch and in any order. This type of line is feasible when no setup time is needed when moving from one model to another.

Assembly line can be paced or un-paced according to the way the material handling works:

- Paced, if a cycle time is assigned and it constrains the process times in all stations. In this case, the workpiece is moved from one station to the next station as soon as the assigned cycle time has elapsed.
- Un-paced, if the workpiece is transferred after the required operations are completed and no time constraint is assigned.

Both systems have advantages and disadvantages. Paced assembly lines guarantee a perfectly controlled cycle time and production capacity but hide the probability of no completion, indicating the risk that some pieces might remain unfinished within the time constraint. On the contrary, un-paced lines guarantee that all pieces are finished but cycle time and production capacity are not perfectly controlled.

The assembly line allows combining operators, materials, machines, and other resources while improving efficiency and reducing production costs. (Jin, et al., 2022) Indeed, the design and balance of an assembly line are the most important issues to be tackled to pursue line efficiency. The first who formulated the Assembly line balancing problem (ALBP) was Salveson in 1955. ALBP consists of assigning tasks to workstations to optimize one or several objective functions (Kriengkorakot and Pianthong, 1955).

In general, assembly line balancing must satisfy takt time and required throughput. Indeed, an assembly line balancing problem consists of assigning tasks among stations in such a way that each station takes the same time, that is takt time (Boysen, et al., 2007) while satisfying production capacity. Line balancing is performed following some steps:

- Breaking the whole production process in sequential steps and drawing a precedence diagram highlighting the sequence of steps.
- Estimating the cycle time for each workstation:

$$CT = \frac{Available\ Time}{Demand}$$

- Calculating the minimum number of workstations needed (NW):

$$NW = \frac{Total\ Tasks\ Time}{CT}$$

- Assigning tasks to the workstations subject to the precedence diagram and cycle time constraint.
- Evaluating the efficiency of the resulting assembly line:

$$Line\ Efficiency = \frac{Total\ Tasks\ Time}{NW\ \times\ CT}$$

Thus, line balancing is usually performed from a mathematical perspective and assuming that the line design can be easily modified according to the results of the optimization problem. In real life, however, redesigning and changing the line is costly and time consuming due to the high number of constraints that an existing layout and a fixed number of stations hide (Qattawi, et al., 2013). This statement encouraged authors (Qattawi, et al., 2019) to introduce lean manufacturing principles such as Value Stream Mapping (VSM) and Kanban system approach to reduce modeling complexities and design constraints. As most of the literature uses complex algorithms to solve ALBP, Qattawi, et al. proposed an approach adapting lean manufacturing principles resulting in reduced computational complexity and improved line balancing.

Furthermore, researchers often assume the numerical input parameters to ALBP as given and constant. However, this assumption is often not met in real life due to many reasons linked to product, environment, and unpredictable changes, especially when manual tasks are involved. Therefore, Jin et al. tackle this issue developing a formulation for ALBP that includes the uncertainty of tasks execution times typical of manual assembly lines.

3 Context

Ingersoll Rand Italia is placed in Vignate and here, every year around 200 centrifugal compressors are produced and sold to companies worldwide. Indeed, the Italian plant of the company is specialized in the production of centrifugal compressors which are available in 3 main models:

- CENTAC:
  The 100% oil-free centrifugal air compressor is the most efficient and reliable on the market, offering up to a 15% capacity advantage over competitive compressors. Thanks to its compact design it can be installed wherever needed. This type of compressor is the top one product of the Vignate plant. The main frame produced in the Vignate plant is the C700.
- TA
  Turbo-Air centrifugal compressor allows easy, low-cost installation and operation. TA is one of the most efficient oil-free compressors at full load, part load or no-load assuring power savings which can significantly speed up the payback of the initial investment. This type of model was introduced in Vignate plant 4 years ago.
- NX
  Turbo-Air Next Generation centrifugal compressor was designed with extensive engineering processes that exploit the latest innovations in technology and computational methods.
  This type of model was introduced in the Vignate plant 2 years ago.

Sometimes an extra-ordinary production may occur at the Vignate plant. Indeed, a different type of compressor, the rotary one, may be requested and assembled inside the plant. It is a rare case, happening not more than once a year.

Rotary compressors are a standard type of compressors if compared to the centrifugal ones which are highly customized. Rotary compressors mainly differ from centrifugal ones for the compression technology: centrifugal compressors are characterized by the impellers, while the rotary ones work through an endless screw. In addition, rotary compressors are used mainly in industrial applications, while centrifugal ones in the oil and gas sectors.
Rotary compressors are available in 2 main models:

1. Nirvana:
   this type of rotary compressor is referred to as IRN, which stands for *Ingersoll Rand Nirvana*. Nirvana compressors are oil-free and air cooled, with a matching variable speed inverter and hybrid motor, providing reliability and energy efficiency at all speeds.
   Some sub-models are produced and are divided in three classes:
   - NOF 1
     The acronym stands for Nirvana Oil Free.
     This model of Nirvana is offered in 2 varieties according to the power: 37 kW and 45 kW.
   - NOF 2
     The acronym stands for Nirvana Oil Free.
     This model of Nirvana is offered in 2 varieties according to the power: 55 kW and 75 kW.
   - NOF 3
     This model of Nirvana is offered in 4 varieties according to the power: 90 kW and 110 kW, 132 kW and 160 kW.

2. Sierra
   It is an oil-free rotary screw compressor ensuring high productivity and 100% oil free even in the most critical applications.

As aforementioned centrifugal compressors are highly customized, thus they are produced following an Engineering to Order (ETO) strategy in Vignate.

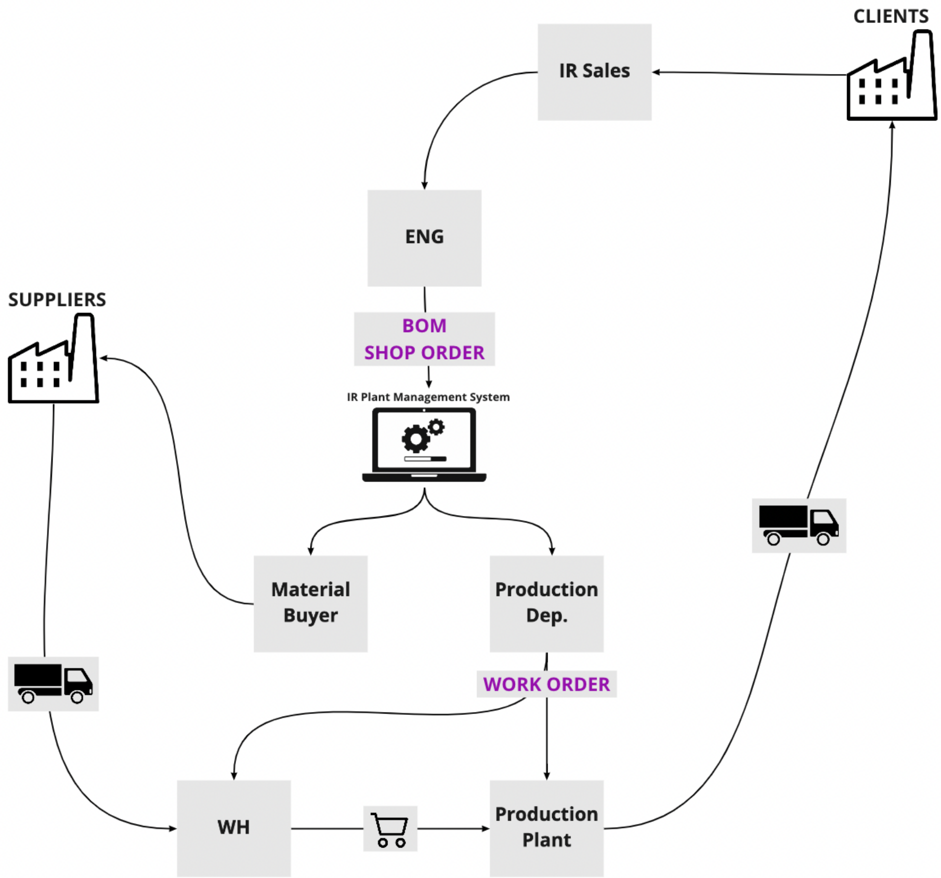


Figure 8: Flows of Information and Materials in IR

Ingersoll Rand's business clients send their order to Ingersoll Rand Sales Department, which releases the information to the Engineering Department and to the Planning one. The latter is responsible for production planning and forecasts and sends the demand input to the management system. The former deals with all the engineering-related activities such as product technical drawings, product modifications, product bill of material (BOM). All these technical information provided by the Engineering Department are uploaded on the Ingersoll Rand international PLM software. From here, any Ingersoll Rand plant around the world can download and then upload the Bill Of Material of each product on the plant specific management IT system. When the Engineering Department receives the order, the BOMs and the shop order are uploaded on the management system of the plant. Once the BOM and shop order appear on the management system, the Material Buyer Department is responsible for getting in contact with suppliers to assure the replenishment of required raw materials and components to the warehouse. At the same time, the Production Department releases the work order to the production plant and to the warehouse. The warehouse downloads the work order information from the system, gathers all the required components and prepares the materials-kit specific for the ordered compressors and transports it to the production plant. The Vignate production plant is organized as follows:

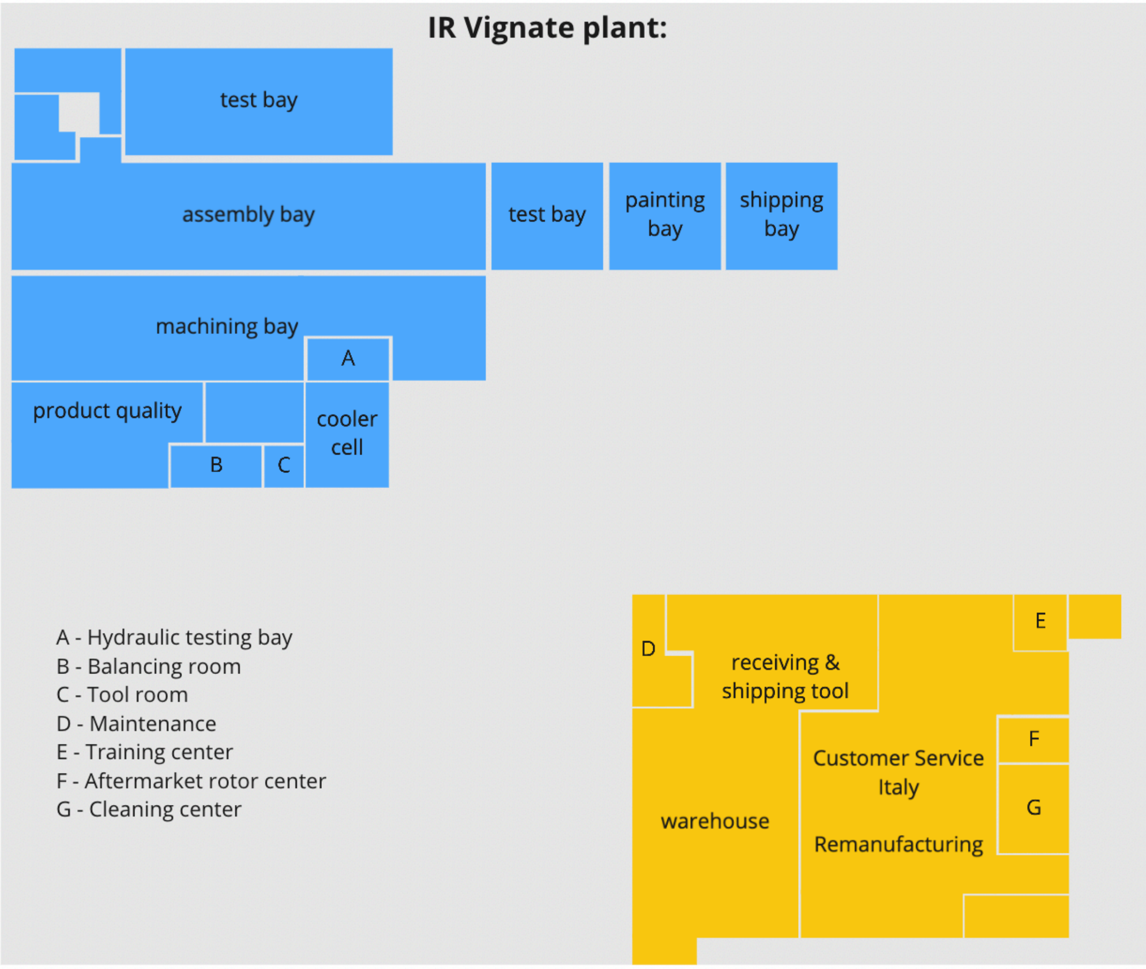


Figure 9: IR Vignate plant

The machining bay is dedicated to the production of the main structure of the compressor from zero. Indeed, here the skeleton of the compressor is processed starting from cast-iron, the cooler (refrigerator) is assembled, and the rotor undergoes a milling process. Parallel to the machining bay, the assembly bay is positioned. Here, the area is divided into two subareas. One is dedicated to the assembly of the air-end of the compressor, that can be seen as its internal structure. The other area is dedicated to the assembly of the package of the compressor. In front of and next to the assembly bay, two test bays are placed. The one next to the assembly line consists of 9 dedicated positions to test small-medium compressors. The test bay in front of the assembly line is used to run tests on particularly big compressors. Going beyond the test bay, compressors go through the painting process and then enter the shipping bay where they are prepared for the delivery. In addition to the areas already mentioned, other sections of the plant are dedicated to specific activities such as:

- product quality controlling,
- hydraulic testing of the skeleton in cast iron,
- balancing of rotors
- metalworking (tools room).

Moreover, the Vignate IR warehouse hosts a remanufacturing area where old compressors are brought to a new life.

The Lean tool selected to perform the project work is the problem-solving A3 framework. As already stated, the A3 is a tool for supporting problem setting and problem-solving. Therefore, it helps in understanding the problem, promoting solutions to the problem, and developing a continuous improvement culture.

The problem-solving A3 foresees 8 steps. In the following chapters, each step of the A3 applied to the project is tackled.

4 Problem Background

As already stated, Ingersoll Rand Italia is specialized in a highly customized type of compressor, the centrifugal compressor, of which it produces around 200 pieces per year. Following the merger with Gardner Denver in 2020, Ingersoll Rand's top management took some business decisions that led to the shutdown of some plants around the world. It is due to this that in 2020, the Ingersoll Rand plant placed in the Czech Republic closed. The Czech plant was specialized in a different type of compressor, the rotary compressor, which is far less customized than the centrifugal compressor and is indeed a standard product.

In the initial phase after the Czech plant shut down, the top management decided to assign the production of rotary compressors among the remaining European plants. In this context, the plant in Vignate introduced the rotary compressors in its product portfolio.

Ingersoll Rand Italia rarely faced the production of rotary compressors in the past. Workers in Vignate recall producing around 20 rotary compressors in 12 years. In those sporadic cases, they would build a task force to take care of that extraordinary production. Even after the Czech plant shutdown, Ingersoll Rand Italia kept using the same strategy: anytime an order for rotary compressors was received a dedicated team would be created.

It is in 2021 that things changed: Ingersoll Rand's top management decided that the whole demand for rotary compressors would be sustained by the Italian plant. Indeed, the planned production for rotary compressors was set to 20 units in 2022 and should reach 60 units in the following years. Once the Vignate plant will stabilize its know-how and its production capacity of rotary compressors, it is expected to reach a yearly output of 300 compressors.

Being both the plant and the resources completely specialized in centrifugal compressors, the company launched a project aiming to define the assembly line dedicated to the new product, starting from the model used by the Czech plant, and optimizing it through the exploitation of the lean principles.

4.1. The Problem

The Czech plant of Ingersoll Rand used a 5 stations assembly line dedicated to rotary compressors. An operator was assigned to each station and worked simultaneously with operators of the other stations. The production flowed at a rhythm of 4 hours per station.

In Vignate, anytime an order for rotary compressors was received a task force would be created, and the assembling of those extra-ordinary products would take days to be completed.

It is clear how this strategy is no more sustainable and convenient for Ingersoll Rand Italia due to the new expected yearly output: 20 compressors for 2022, 60 compressors per year as a target and hopefully reaching 300 compressors per year.

Figure 10 represents the Problem Background section extracted from the A3 framework of the project.

As already explained in the Introduction of this master thesis, the Problem Background must answer to the question "Why is it a problem". The Czech plant used to assemble a rotary compressor taking 4 hours per station. Once the plant closed in 2020, the production of rotary compressors was moved to the plant in Vignate together with the assembling procedures and the components that were left in the Czech warehouse. The Italian plant had only occasionally faced the production of rotary compressors. If compared to the 200 centrifugal compressors produced per year, the rotary production was extremely marginal in the previous years.

Comparing the production rhythm of the Czech plant, which employed 4 hours per station, to the 3.5-times slower rhythm of the plant in Vignate, together with the 35-times bigger expected output, it is clear how an improvement action is needed.

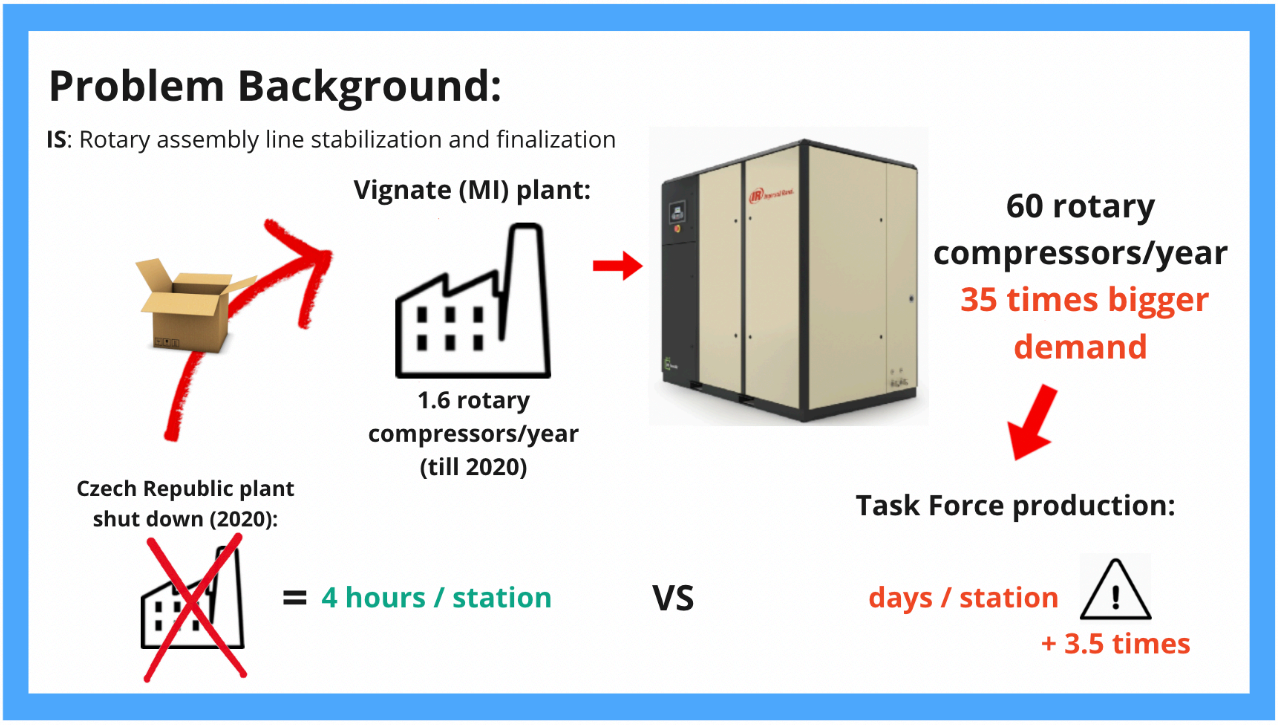


Figure 10: Problem Background Box extracted from the A3

4.2. Stakeholders

This project work involved various stakeholders of the company, as follows:

- The Manufacturing team: the one directly involved in the execution of the project. The manufacturing team is led by Eng. Francesco Audino and includes Eng. Sara Cremonesi, the company tutor of this master thesis.
- The Assembly Department is led by Adriano Verderio.
- The Package Area leader Carlo Albani and its operators make the selected team for the assembly line.
- The Warehouse is led by Alessandro Balzaretti.
- The Material Buyers are guided by Bruno Romani.
- The Quality Department is run by Federico Colombi.

5 Problem Breakdown

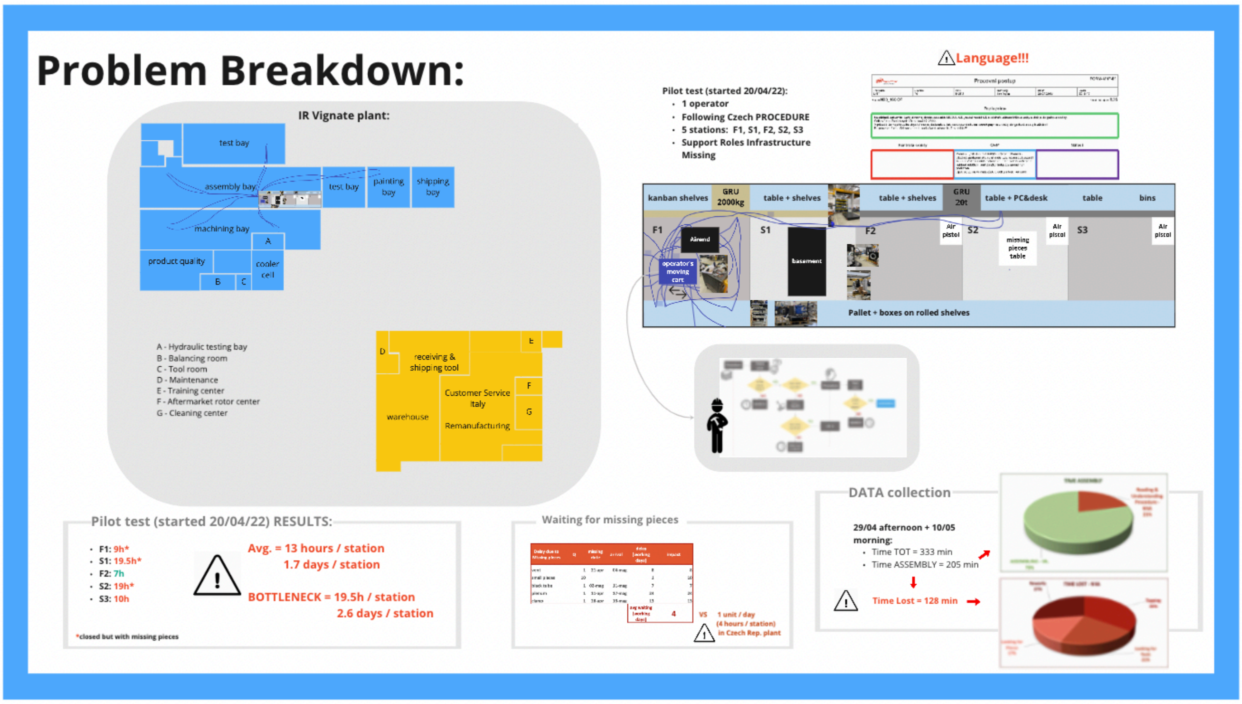


Figure 11: Problem Breakdown Box extracted from the A3

In this chapter, the current situation of the Vignate plant regarding rotary compressors is presented in order to better and deeply understand the problem.

As already mentioned, the plant in Vignate is divided in several specific areas dedicated to different tasks:

- Machining, where cast iron is processed to build the skeleton of centrifugal compressors.
- Assembly, where pieces are assembled to build the final compressor.
- Two test-bays, where compressors are tested before reaching the customer.
- Painting, where cast iron components are painted, before the assembly.
- Shipping, where compressors are finished and prepared for the delivery.
- Quality.
- Warehouse and re-manufacturing area.

Focusing on the Assembly bay, the area is divided in 3 parts:

- One is dedicated to the assembly of the air-end of centrifugal compressors. The air-end is the part of the compressors consisting of the motor and the skeleton made from cast iron in the machining bay.
- The next area is used for assembling the package on the air-end.
- Then, there is the area where the rotary assembly line will be positioned.

At the beginning of the project, this area had been already sketched but appeared chaotic and smaller than it really is. Indeed, the area still hosted on one side, covering the whole wall, many shelves containing components not related to the rotary compressor, but used in the assembly of all the other ones, some tables storing messy documents and a desk with a PC where the Assembly Team Leader runs his daily activities. Furthermore, a table holding small components was placed in the middle of the area. On the opposite side, pallets and rolled carts storing materials needed to build a rotary compressor were positioned. The area was equipped with 2 different types of cranes for lifting heavy objects (500 kg and 20 T) and 3 air pistols.

The day after the beginning of the project in Ingersoll Rand Italia, the stakeholders decided to launch the first assembly of the NOF 3 rotary compressor in the new dedicated area. It was the perfect chance to start analyzing the problem by directly observing it during a pilot test.

The plan was to let 1 operator assemble the product following the same procedure used by the Czech plant and to complete each assembly station within a day (7.5 working hours).

Therefore, five stations were outlined on the floor as suggested by the procedure. The sequence of stations in Czech procedure is: F1, S1, F2, S2 and S3. Then, the procedure was printed and given to the operator. Here, a first issue showed up: the procedure had not been translated and was in the Czech language. This would prevent the operator to have the possibility to read and understand it and would leave him without a reassuring guide during his tasks. Indeed, the procedure presented pictures and drawings that could have showed to the operator how the tasks should be executed. Furthermore, in case of any doubt, the operator would not have the possibility to read the procedure and find an answer.

An additional issue was the absence of an infrastructure of support roles, thus responsibilities where not clearly identified.

5.1. The Pilot Test

The 21st of April, the pilot test officially started. The main activity which was performed was to follow and observe the operator throughout the whole assembly of the unit. This allowed the mapping of all the performed activities, assembled components, and used tools. But even more, it was crucial for discovering issues and gathering suggestions from the operator that could help in easing the whole assembly and avoiding wasted time.

At the same time, data needed to draw a Spaghetti Chart were gathered.

In the following figure, the Spaghetti Chart for the first station is represented. It must be specified that for sake of simplicity and clearness of the graph, this chart was drawn just for the first station, but it can reasonably approximate the situation of the other stations too.

As it can be seen, the Spaghetti Chart appears messy, and some movements are highly repetitive. Indeed, the operator frequently moved back and forth from his personal tool cart where he kept the procedure and the component being assembled. Furthermore, he frequently moved out of the assembly line towards other departments in search for tools that were not on the rotary assembly line, or he walked through the other stations to reach the crane base needed to lift heavy objects. The numbers on the movement lines are an estimation based on the number of operations performed in the first station.

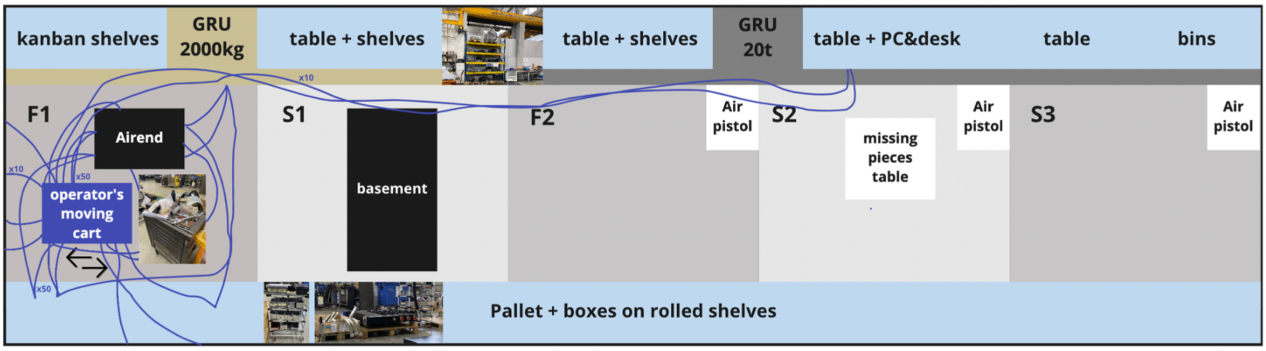


Figure 12: Current Line layout & Spaghetti Chart

The operator flow of activities was analyzed and represented in a summarizing diagram, as follows:

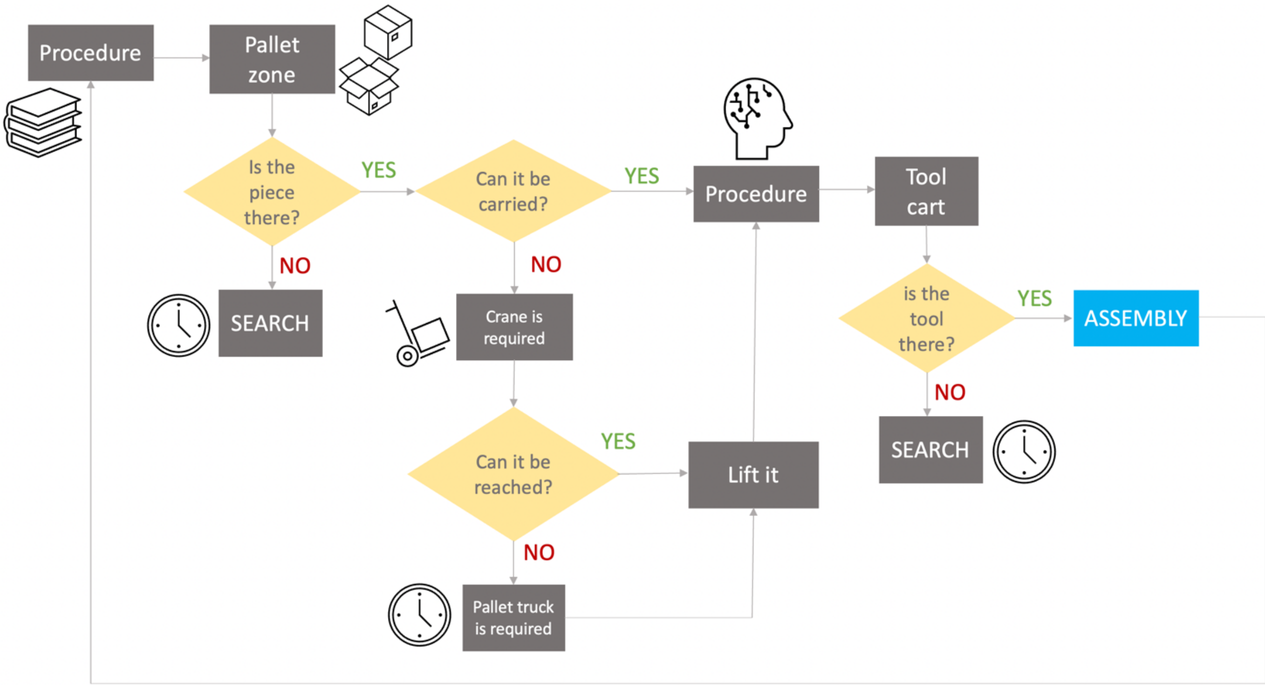


Figure 13: Operator's Flow of Activities

The operator started by reading the procedure. The procedure is divided by stations and each specific procedure is divided in numbered operations to be executed. Each operation is associated with the code, the description, the quantity of the components to be used in the operation and drawings and/or pictures showing what the operator must do. A written description of the activity is also provided. Yet, as already mentioned, being in Czech it was completely useless during the pilot test.

Ingersoll Rand Inspiring Progress	Pracovní postup				FORM-MNF-01
Pracoviště L4F1	Operace 10	CPN NOF3	Technolog Jan Vojta	Datum 20.07.2018	Revize 2018-17

Product N90_160 OF — Výrobní čas [min] 8.05

Popis práce

Na základě sekvenční karty si nechej dovést ze skaldu MODUL A/E ,rozbal modul A/E a odstraň veškeré křížové zátky a vlož je do igelitové složky.
Celkové množství žlutých zátek musí být 23 Ks.
V případě, že nějaká zátka chybí přímo od dodavatele, tak napiš poznámku na kousek papírku a vlož ji do igelitové složky k zátkám!
Po provedené montáži komponent musí zůstat celkem 8 děr volných !!!

Kontrola kvality	Ověř	Nářadí
	Zkontroluj,zda-li není AIREND poškozen.Zkontroluj všechny zaslepení otv. na airendu, zda nejsou poškozené! Bude-li některé z nich poškozeno, je třeba toto poškození nahlásit oddělení kontroly!Zkontroluj zda airend není poškozen. Ujisti se, že na Airendu zůstalo celkem 8 děr volných!	

Figure 14: Extract from the Czech Procedure

Once given a first glance at the operation, the operator moved to the pallet zone on the side of the area to gather the components needed. If he did not find it, he had to search for the item, wasting some time doing so. Otherwise, he would proceed. If the item was heavy, he would have to use the crane. If the crane did not directly reach the component, he would move through the other departments in search of the pallet truck.

Once he gathered the required components, he went back to the procedure to read it again and understand what he had to do. Then, he searched for the tools needed inside his tool cart drawers. If he did not find the tool there, he would move through the other departments searching for it, wasting some more time. Finally, he moved to the sub-product to assemble the next items. This process went on and proceeded like this for the entire procedure execution.

5.2. Pilot Test Results

On the 18th of May, the assembly of the compressors under analysis was completed.

From the beginning, it was clear that the pilot test was not going as planned. Indeed, the plan was to conclude a station every day. Therefore, in 5 working days, the assembly was expected to be completed. Instead, the pilot test lasted almost a month.

If we focus on the duration of each station, it was observed that:

- the station F1 took 9 hours to be completed.
- S1 lasted 19.5 hours, which means more than 2.5 days, if we consider 7.5 working hours per day (as in the Vignate case).
- F2 was completed within 7.5 hours.
- S2 lasted 19 hours, which means around 2 and a half days.
- The last station, S3, took 10 hours to be completed.

It must be specified that the durations do not include the days in which the assembly was stopped due to the absence of required components.

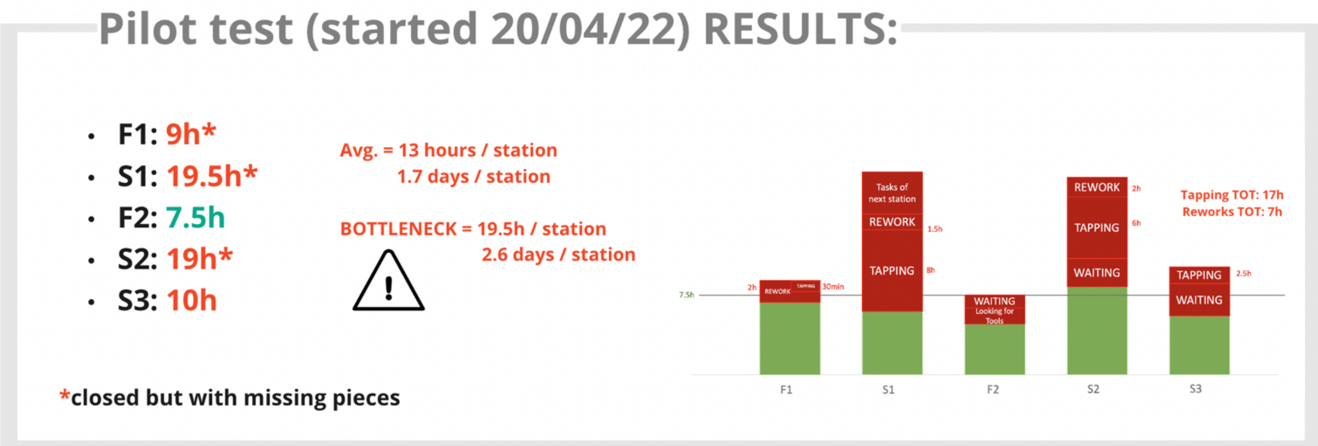


Figure 15: Pilot Test Results extracted from the A3

The average duration of a station was 13 hours, which means 1.7 days, almost twice the target (1 day). Furthermore, looking at the bottleneck station, the slowest one, it flowed at 19.5 hours per station, which are 2.6 days. It is evident how the situation is serious, since all the line will flow at the bottleneck speed.

Wishing to have a closer look at the data, a qualitative analysis of what made the stations take more time than planned is proposed in the following figure:

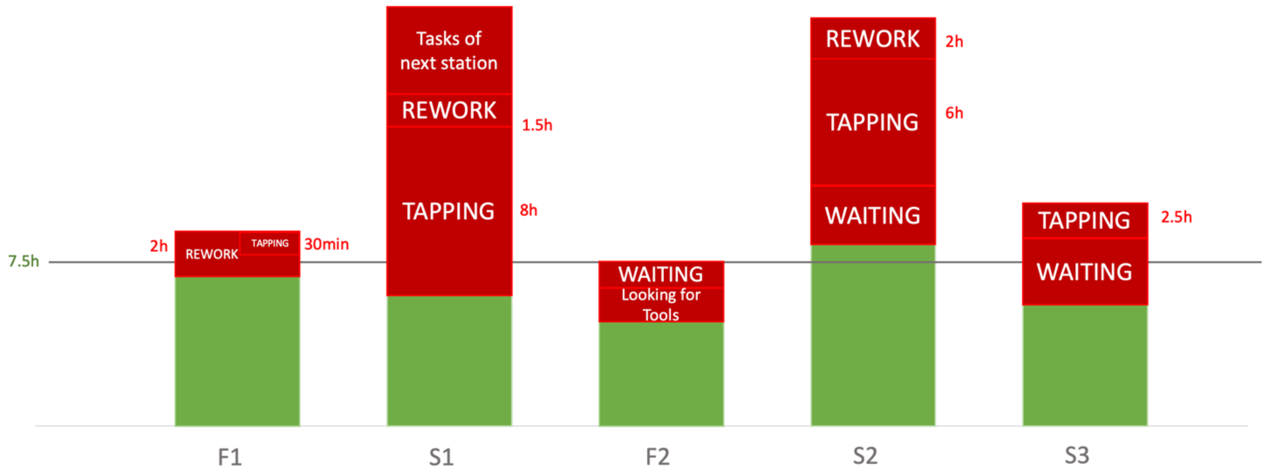


Figure 16: Pilot Test: stations durations and wasted time

The assembly procedure of the first station F1 was surprisingly completed within 7 hours. However, 2 hours of reworks must be accounted since during the assembly of the motor on the air-end, a screw broke inside the motor. This obliged the operator to disassemble the motor, remove the screw, clean the hole, and start again the assembly of the motor.

The second station S1 overcome the 7.5 hours' time window mainly due to four issues:

- Rework: at first the operator positioned the air-end on the basement in the wrong place. This was caused by a difficulty in understanding the procedure. Indeed, the drawing did not show clearly which was the precise position for the air-end to be placed on the basement.
- Looking for Pieces: during the assembly of the second station, the operator faced the missing of some components which compelled him to call for support from the production office, which asked the warehouse to bring the components. This generally absorbed half a day. Still regarding the components, in some cases the code on the component provided by the warehouse did not equal the one on the procedure. In that case, the operator had to inform the production office and wait for their validation.
- Tapping: this is a huge problem observed throughout the whole assembly. Indeed, the operator had to tap holes in many components that are provided already painted by the supplier. What happens is that during the painting phase at the supplier, the holes that should host a screw lose their tapping capacity due to the paint that covers

the holes. Furthermore, the procedure provides just non-self-tapping screws. This way the operator is obliged to tap the holes to avoid the breakage of screws. This activity was done manually and took a huge amount of time. An analysis of manual tapping effort has been performed. All the components that needed tapping were mapped and the number of holes counted, resulting in 27 components with a total of 247 holes to be tapped. Considering that the operator spent 1.5 hours to tap a component that had 18 holes and 20 minutes to tap a component with 6 holes, the operator employed on average 4.2 minutes to tap a single hole. Multiplying this average value by 247, it is estimated that more than 17 hours were spent in manually tapping during the pilot test. Then, dividing the holes among the stations considering in which operation the related component is used, using the same method, an estimate of tapping time per station was computed. It resulted in 30 minutes in F1, 8 hours in S1, 6 hours in S2 and 2.5 hours in S3. We must specify that the 30 minutes of tapping during F1 were not executed during the pilot test and that is the reason why screws broke and caused 2 hours of rework. Therefore, in *Figure 16* the tapping time is already included in the time spent reworking.

- Unexpected Anticipation of some task of the next station:
  The procedure of the second station 5 times recalls for groups of components that should be pre-assembled in the next station. Therefore, the operator executed those pre-assemblies of the third station directly on the second station, anticipating them.

This last issue can be the direct reason for the shortest execution time of the third station. Even though the operator waited for the missing pieces, had to tap holes on components and moved through the other department to search for tools, the assembly was completed in 7 hours. This may be explained by the fact that some group of components had already been assembled in the previous station.

Moving on to station of S2, this again lasted more than 2 and a half days. Again, many hours of tapping where needed. In addition, two reworks took place during the assembly at the third station. One was due to a component needed but not mentioned on the procedure. The operator followed the procedure but was then informed by the production office that an additional component was needed because it was mentioned in both the BOM and the drawing. The second rework followed a mistake in assembling a component due to an unclear drawing in the procedure and the consequent difficulty for the operator to understand what to do.

The last station was executed very slowly due to the absence of the main components. The operator had to carefully choose which operation he could execute without those missing components. Also in this case, tapping employed a part of the station time. An additional point that was observed in this station is that the last part of the procedure consists of a series of operations requiring to attach a label on the finished product. It is clear how attaching a label takes far shortest time than any other assembly activity.

In addition to this analysis, we must highlight another observed issue. The presence of some obstacles on the floor, such as a heavy pre-assembled component which could not be assembled on the machine due to the missing of a crucial item, prevented the operator to easily move the unit through the stations. Indeed, the assembly was completed on the area dedicated to the second station S1.

5.3. Missing Pieces

As it has already been mentioned, the problem of missing pieces is quite serious. Indeed, they took a quite long time to arrive, from days to weeks, causing the stoppage of the assembly.

As to go more in depth, five components caused delays on the assembly:

- A component called vent was discovered to be missing on the first station F1 in the first day of the assembly, on the 21st of April. Even though the operator immediately informed the office, this piece arrived only on the 4th of May, that is 8 working days later.
- A clamp needed on the second station S1 was discovered to be missing on the 26th of April and did not arrive at all. The machine was planned to be delivered to the customer on the 20th of May. Initially, the clamp was expected to be supplied on the 13th of May, but then the delivery was further delayed. Once it was clear that it would not arrive on time, the operator used another type of clamp already present on the plant, adjusting it, to substitute the missing one and to deliver the compressor on time

to the customer. Assuming the adjusted clamp as the real one, 16 working days were waited to have it.

- The plenum needed on the third station F2 was discovered to be missing before beginning the assembly and even before the starting of the project work. Indeed, when on the 11th of April the warehouse checked if all the material necessary to build the compressor had been supplied, it found out that this component was missing. The plenum only arrived on the 17th of May, that is 24 working days later.
- A black tube needed on the fourth station S2 was discovered to be missing on the 2nd of May and arrived 7 working days later.
- Furthermore, some other small pieces such as screws or washers were discovered to be missing throughout the whole assembly. For these small components, the supply is much easier and faster. Indeed, they are stored in the warehouse in huge quantities and using Kanban boxes. Therefore, when the operator discovered there were some of them missing, he would just call the warehouse and have them supplied in just one working day.

In the following table, information about missing pieces is summarized.

Delay due to Missing pieces	Q	missing date	arrival	delay [working days]	Working Days of Waiting for Pieces
black tube	1	02-mag	11-mag	7	7
vent	1	21-apr	04-mag	8	8
small pieces	10			1	10
clamp	1	26-apr	19-mag	16	16
plenum	1	11-apr	17-mag	24	24

Table 1: Missing Pieces and their impact

As it can be easily understood from the values, the impact of a missing pieces is heavy on the capability to assemble a compressor respecting the constraints of each station to be completed in one working day. Ideally, a compressor should be completed every working day, if we consider 5 operators working simultaneously and completing each station in 1 day, as in the Czech plant. If we compare the objective to assemble a compressor per day with the 24 working days waited to have the plenum delivered, or the 16 working days for the clamp, or even just the 7 days for the black tube, it is evident how missing pieces are a huge obstacle to on time assembly.

A HINT OF DATA: NVA vs VA classification

It is now clear how many different issues prevented the assembly to be completed in a reasonable time. If initially the plan was to conclude a station in a working day, looking at the rhythm of the well-stabilized Czech line, and thus to have the compressor completed in 5 working days, it unexpectedly was finished in a month.

A hint of a data collection was performed and then analyzed to map the activities executed during the assembly to understand which are NVA (Non-Value Adding) and which are VA (Value Adding).

On the afternoon of the 29th of April and on the morning of the 10th of May, while the operator performed assembly tasks, all the activities were mapped and timed.

Here, the results follow.

The total time monitored was 333 minutes, or 5.55 hours. Out of the monitored 333 minutes, only 205 minutes were spent assembling. The remaining 128 minutes were spent performing non-value adding activities such as:

- 35% of wasted time was spent tapping holes.
- 27% was spent on reworks due to some mistakes.
- 21% was spent walking through the departments and looking for tools.
- 17% was spent looking for pieces, due to different codes between the item on the pallet and the same item on the procedure, or due to the missing of the piece, etc.

If we look closer to the time spent assembling, a portion of it, precisely 21%, was spent by the operator reading and trying to understand the procedure. Even this last component of time is classified as NVA.

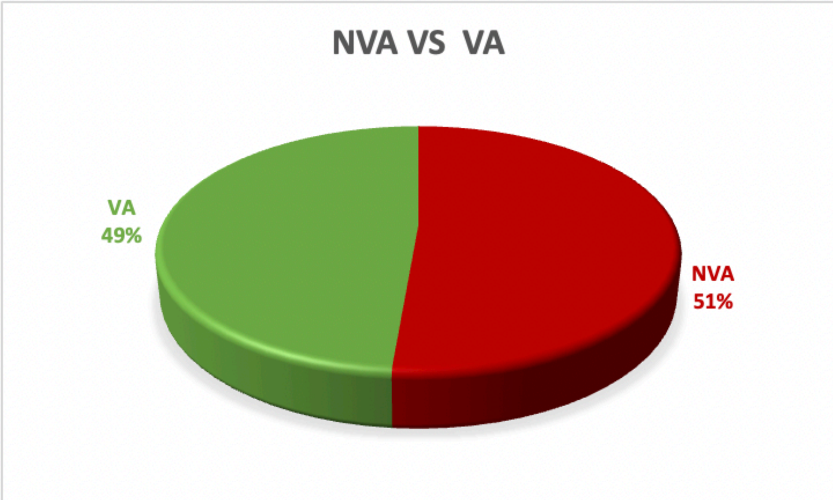


Figure 17: NVA vs VA

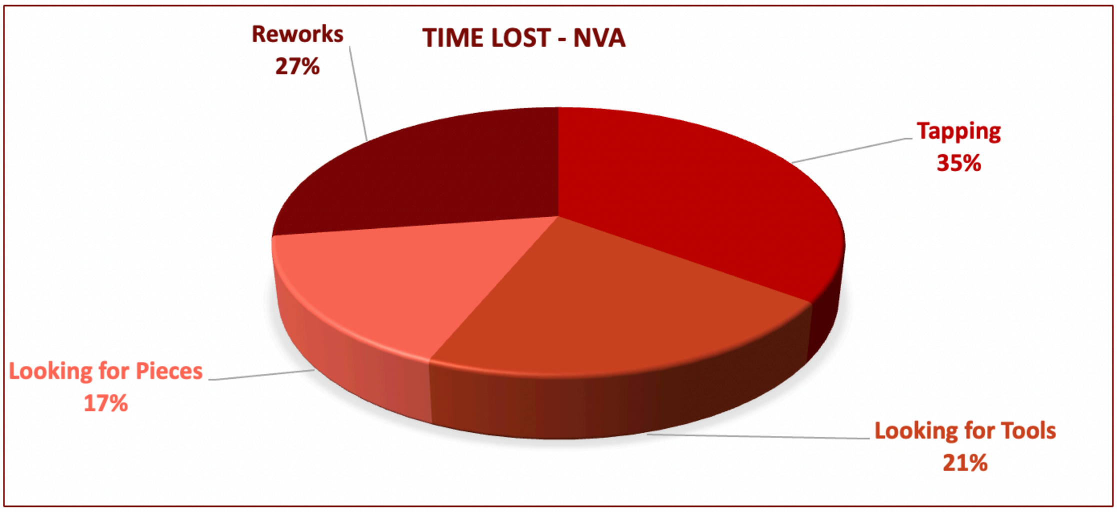


Figure 18: Pie Chart of Time Lost

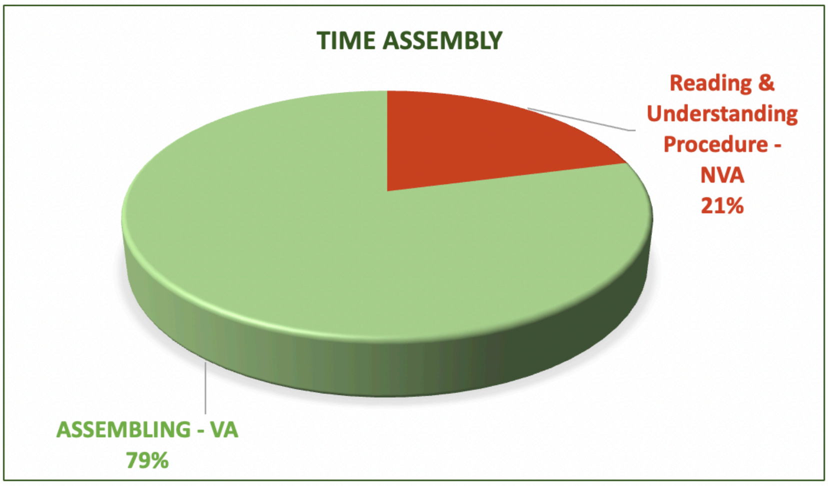


Figure 19: Pie Chart of Assembly Time

6 Target

Once analyzed the problem, desired targets were defined together with the stakeholders.

The objective was to optimize and customize the assembly line dedicated to rotary compressors starting from the model and procedure used in the Czech plant.

In this view some quantitative targets were outlined.

Starting from must-have targets, two main goals must be achieved by the solution proposed by the project:

- The first objective is time-related. Each station must be concluded by 7.5 hours, which means within a working day. The Czech standard was 4 hours per station, but it was reached in a plant completely dedicated to the rotary product and consolidated in time, thus the assembly line was stable and worked at full speed. Furthermore, the Czech model relied on many pre-assembly, completed before the starting of the line. In Vignate the rotary line will be first created during the project work. Furthermore, the results from the pilot test are far from the target value. Therefore, it is reasonable to start by assigning a larger time to conclude the station compared to the Czech model. Of course, as time goes by and experience and know-how are built, this time may be reduced.
- The second objective relates to the stabilization of the line. It is evident from the analysis of the problem that the current situation is everything but stable, therefore stakeholders expect the new line to be stabilized through the reduction of reworks and the introduction of a method to monitor the performance of the upcoming assembly line. To quantify the reworks reduction, the time unit is considered. The target is to reduce the time spent reworking by 45%.

  While in order to monitor the performance of the assembly line, stakeholders expect the definition of an SQDIP board, a lean tool where safety, quality, delivery, inventory, and productivity indicators are periodically reported.

Moving on to the nice-to-have targets, stakeholders would be pleased if the must-have targets would be overcome and deepened:

- Regarding the time-related target, reaching an assembly rhythm of 4 hours per station as in the Czech model would be delightful.
- The goal of line stabilization can be deepened by creating a clear work instruction that could result in a 45% reduction of the time spent in understanding the procedure.
- An additional point could contribute to further satisfying the stakeholders. Therefore, a third nice-to-have target has been defined: creating a more efficient layout. In the analysis of the problem, some examples highlighted how the current area can be improved: obstacles on the floor, heavy components placed far from the crane, repetitive back and forth movement inside the station, frequent exits of the operator from the area to look for tools and looking for tools on the line that are hidden in the messy cart. In this sense, the layout can be made more efficient. To quantify this target, the number of movements out of the area and the time spent looking for tools are used as indicators. Therefore, in the to-be layout the movements out of the rotary assembly line area should be maximum 2 and the time spent in looking for tools should be reduced by 50%.

Focusing on the time related targets, the proposed target translates into a 64% reduction of hours per station starting from the current situation represented by the bottleneck that is 19.5 hours per station. While the nice-to-have target enlarge this reduction to 79%.

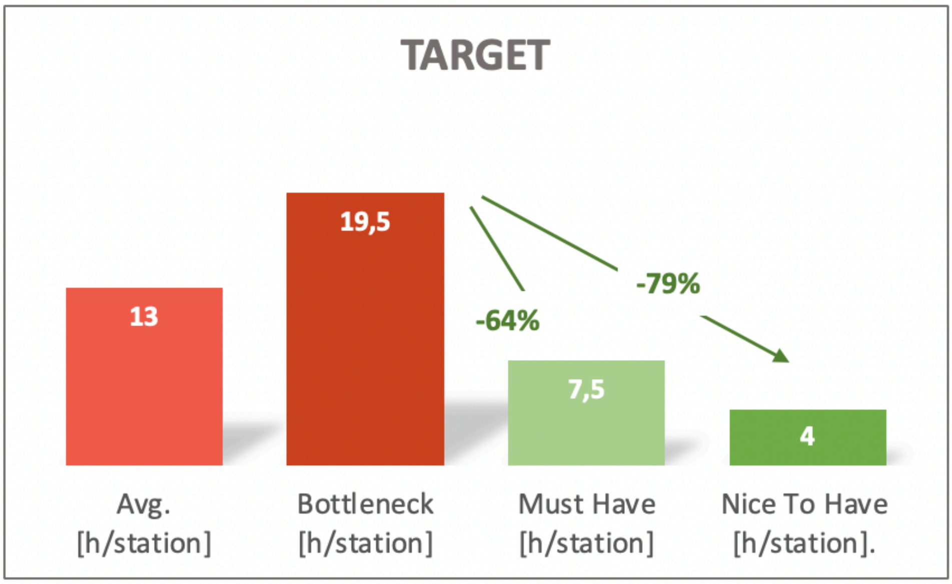


Figure 20: Targets and Current Values in comparison

7 Root Cause Analysis

Once analyzed the background of the problem and the current situation and set the targets, the Root Causes analysis was performed, and it is reported in the following chapter.

As mentioned in the introductory chapter to this master thesis, the Root Cause Analysis is a problem-solving technique allowing to dig into the problem characteristics to identify the root cause, which is the primary cause to the problem. Discovering the root cause is crucial to define the appropriate countermeasures to solve the problem. Indeed, a countermeasure must remove the root cause to permanently solve the problem.

In order to perform the Root Cause Analysis some tools are suggested. The Ishikawa Diagram is a graphical and visual tool that helps in classifying causes. The 5 Whys Method by asking why questions allows to trace back from a potential cause to the root one.

In the case at hand, the Ishikawa diagram was performed, and 6 classes of causes were selected: People, Process, Equipment, Materials, Environment and Management. The resulting diagram is the following:

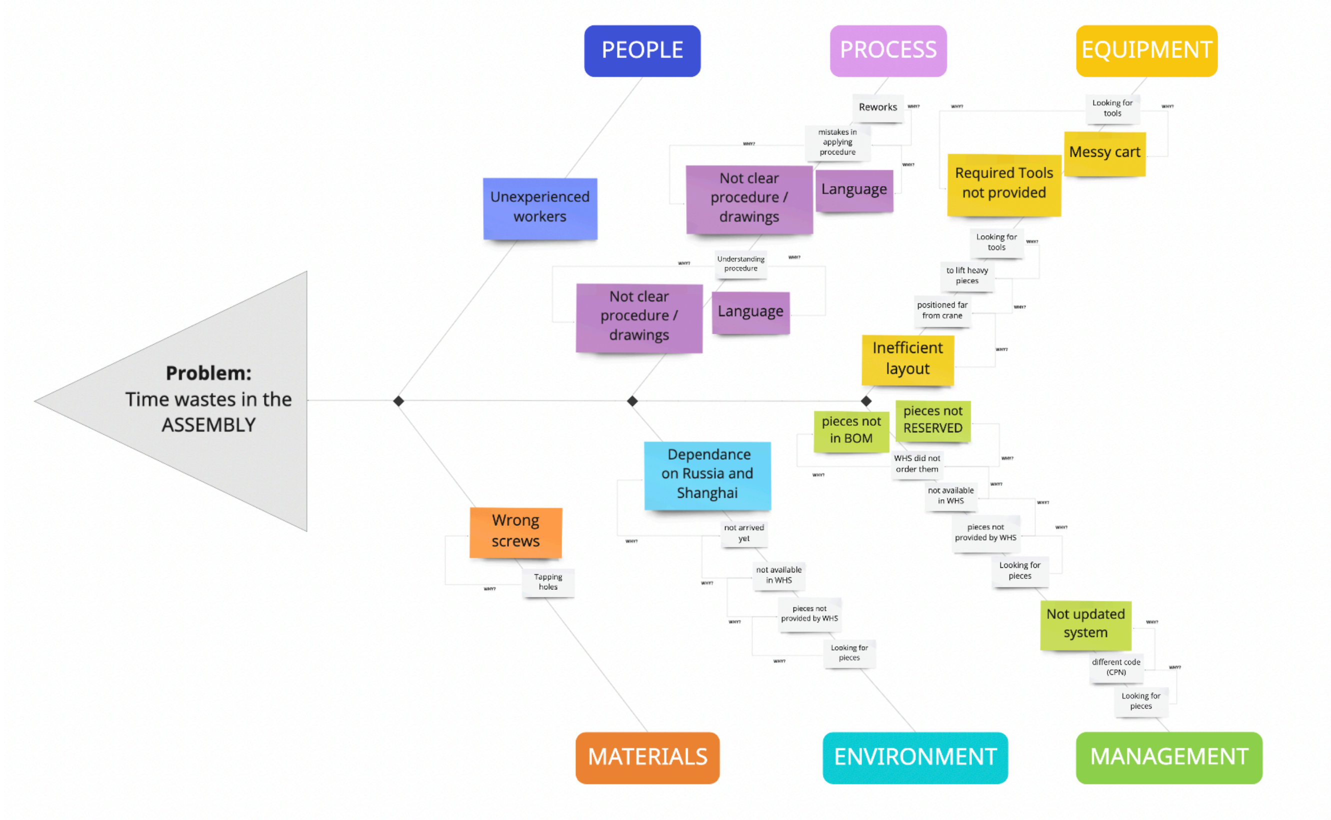


Figure 21: Ishikawa Diagram of the Project

In the resulting Ishikawa diagram, root causes were reached by applying the 5 WHYs method and are highlighted in the same color of the relative class.

As it is clear from the analysis, the main problem can be identified as the huge quantity of time that is wasted during the assembly activities. Therefore, in the head of the fishbone diagram the problem is referred to as “Time wastes in the assembly”.

For this problem, 11 root causes were identified:

- Unexperienced workers in the People class
- Not clear procedure and drawings and language in the Process class
- Messy cart, not provided tools and inefficient layout in Equipment class
- Wrong screws as regards Materials
- Dependance on Russia and Shanghai in the Environment class
- Not updated management system, pieces not in BOM and pieces not reserved as regard Management.

In the following paragraphs, each class of causes is tackled.

PEOPLE

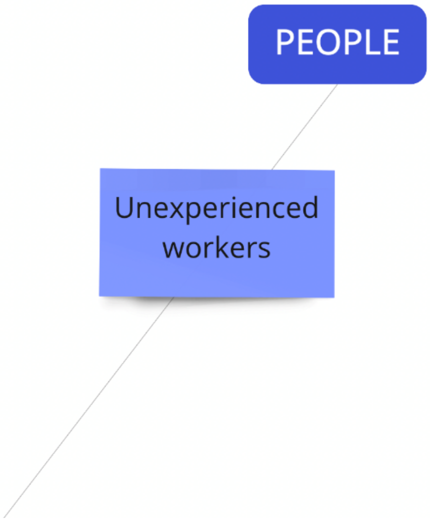


Figure 22: People-bone of the Ishikawa Diagram

Starting from the top left bone of the fish, the class of causes first presented is People. The human reason why the pilot test lasted much longer than expected is related to the fact that it is a completely new product, with a specific procedure and operations, unseen by operators before. Therefore, workers' inexperience in the assembly of the rotary compressor made each assembly operation last more than if it was a known and previously done one.

PROCESS

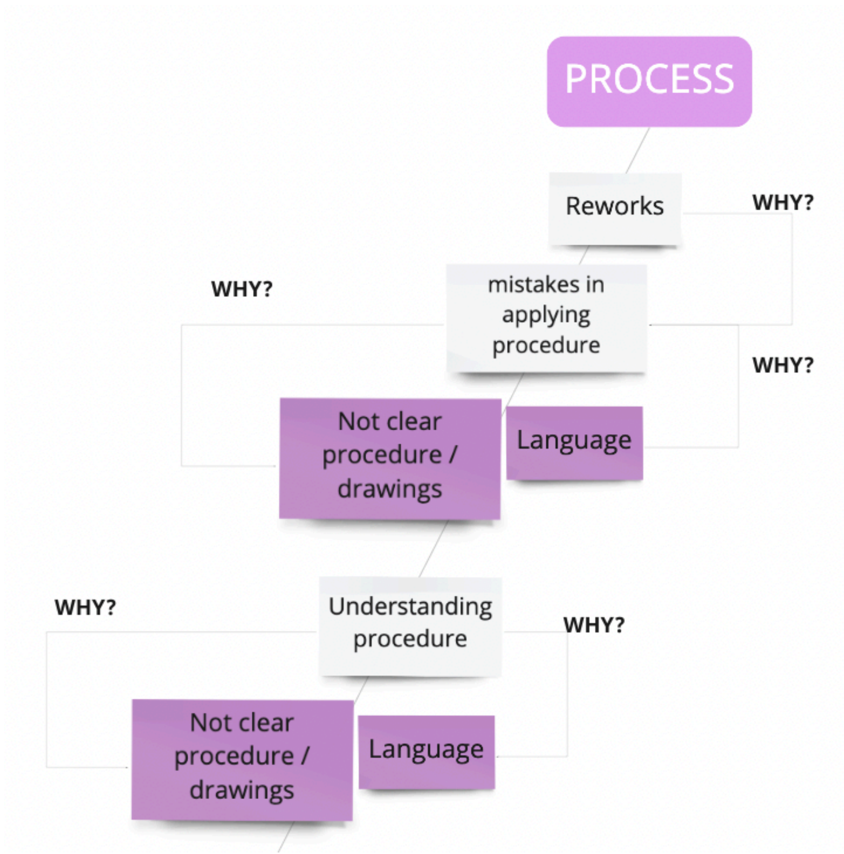


Figure 23: Process-bone of the Ishikawa Diagram

Moving further to the right, the Process class is analyzed. Keeping in mind that the problem is the high quantity of time wasted during the assembly performed as a pilot test, we may ask “which non-assembly activities absorbed time?”. The answers related to the process are two:

- Reworks, and
- Understanding procedure.

For both of them, the 5 Whys method was applied to reach the root cause.

Starting from reworks, they were mainly needed due to mistakes in applying the procedure, and therefore the operator had to disassemble and then assemble again, wasting time. Those mistakes were caused by the unclearness of the procedure and to the Czech language incomprehensibility of the Italian workers in the Vignate plant.

In the following pie chart, reworks executed throughout the whole assembly of the pilot test are quantified and summarized:

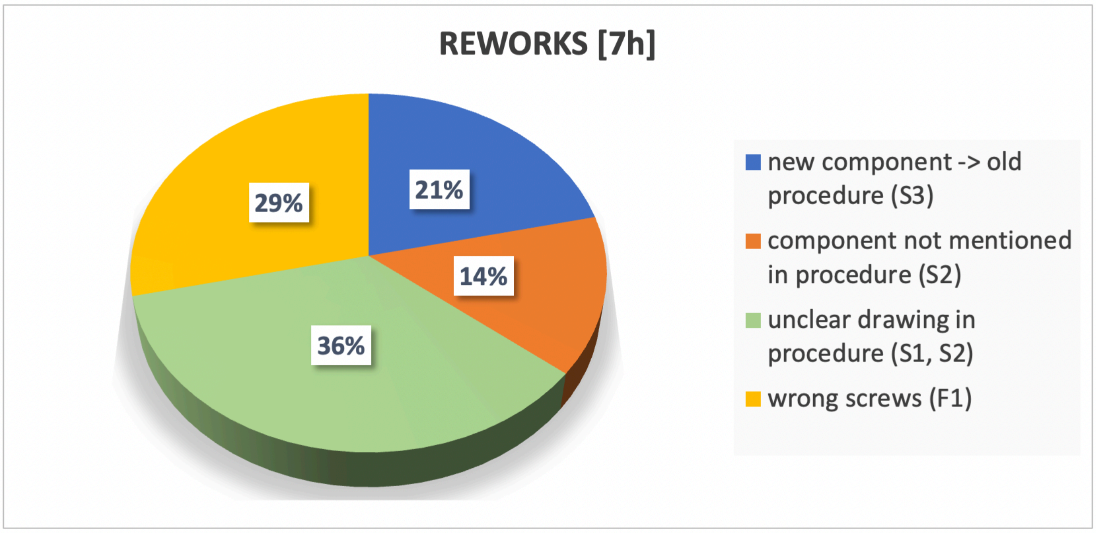


Figure 24: Pie Chart of Reworks

In the whole assembly, 7 hours were spent reworking:

- 1 hour was spent in disassembling a component in order to add a piece that was not mentioned in the procedure but was discovered to be necessary. In this case the procedure had an error in the list of needed components, therefore the operator had to rework.

- 2.5 hours were spent correcting the assembly because it had been wrongly executed by the operator due to unclear drawings. Indeed, the guiding drawing in the procedure did not highlight the holes in which the screw to block the air-end on the basement had to be inserted and the operator failed in the first attempt.
- 2 hours were spent reworking the motor assembly after the screw broke. In this case, the procedure suggested using self-tapping screws, but it was not highlighted, and the operator did not notice this advice.
- 1.5 hours were due to a changed component. The procedure proposed a different type of component from the one provided by the warehouse. This new component was assembled following the procedure, but it was later discovered that it should be assembled by different operations. Therefore, the operator had to rework it. In this case, the cause is that the procedure is old, and the new component is not assembled in the same way. This means that the procedure needed also to be updated.

Moving on to the second activity, the operator spent a lot of time understanding the procedure, what he had to do, and what he had to use as tools and as components. This activity also traces back to the unclearness of the procedure and the drawings and the incomprehensibility of the Czech language for operators.

EQUIPMENT

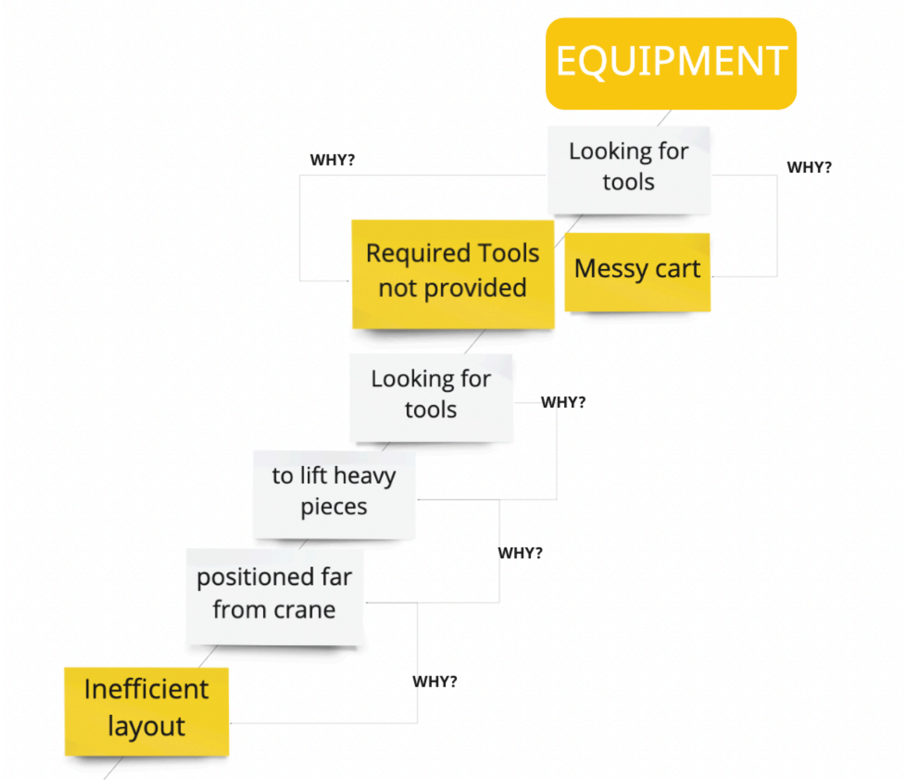


Figure 25: Equipment-bone of the Ishikawa Diagram

As regards the Equipment class of causes, time was waste looking for tools needed throughout the assembly.

The operator looked for tools because he could not find them in his messy cart or because the required tools were not in the line and therefore, he had to move to the other departments to ask for them. Both the activities wasted time.

The operator also wasted time looking for tools such the pallet truck by which he could move those heavy components that had not been placed near the crane. Therefore, the operator had to move to the other departments to look for the pallet truck, move the component to a position that could be reachable by the crane, and then lift it using the crane. The reason why it is far from the crane is because of the inefficient layout.

MATERIALS

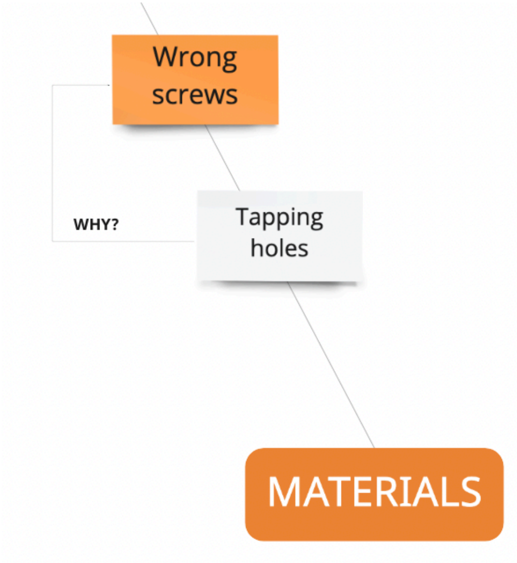


Figure 26: Materials-bone of the Ishikawa Diagram

Moving on to the bottom left part of the diagram, the Material class is presented.

The material-related activity that mainly absorbed time is tapping. Indeed, throughout the assembly 17 hours were spent doing this non-value adding activity.

The operator had to tap holes on many components that are provided already painted by the supplier but that come with the holes that should host a screw lose covered in paint making it impossible to tighten the screw without breaking it. This is because the screws described by the procedure, the Engineering drawings and the BOM are not self-tapping. Then, the root cause is identified with the wrong choice of screws.

ENVIRONMENT

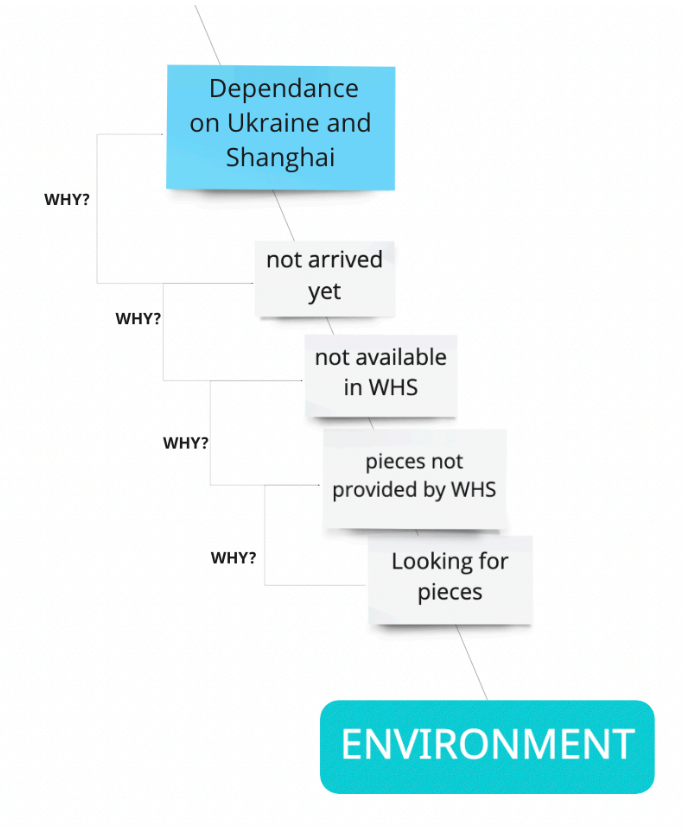


Figure 27: Environment-bone of the Ishikawa Diagram

Another activity that wasted time is looking for pieces.

Indeed, when the operator moved from the procedure to the pallet zone to pick the component, sometimes the required component was not there.

As to investigate why the component was not there exploiting the 5 Whys method, the first answer is that the pieces had not been provided by the warehouse. Going further, the reason why the warehouse had not provided the component is that that component was not available in the warehouse. The reasons for the component unavailability can be two:

- The warehouse had not ordered the component. The further reason will be explained in the next paragraph, regarding Management causes.
- The order for the component had not arrived on time. This is due to the dependence on Ukraine and its steel from which most of the components used in Vignate are made. In addition, the dependence on the critical situation in Shanghai prevents components to leave China by boat. It must be specified that these two environmental-related causes are common to other industries worldwide and will be

hardly solved in the short term. Therefore, they will remain out of the scope of the project.

MANAGEMENT

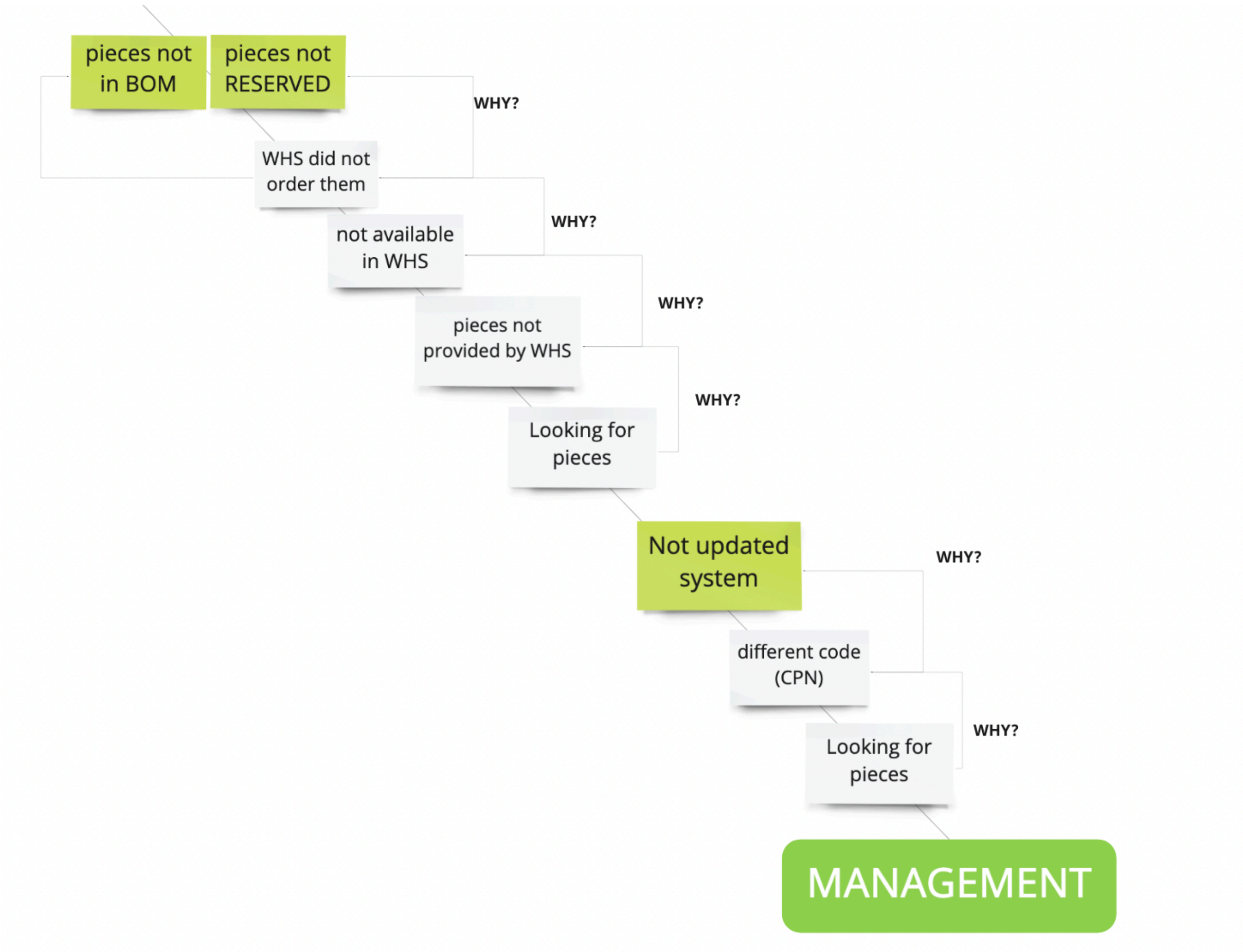


Figure 28: Management-bone of the Ishikawa Diagram

Moving to the last bone, we find the Management class. In this case, the activity which mainly waisted time is looking for pieces. This activity can be investigated further relating it to the management context.

As already mentioned in the previous paragraph, the operator looked for pieces because they had not been provided by the warehouse, because those pieces were not available. Required pieces were not available in the warehouse because the warehouse had not ordered them. The root causes of the missed order of required components by the warehouse is that those pieces were not in the BOM or were not *reserved* in the management system to produce that compressor.

As already mentioned in the Context chapter of this Master Thesis, information such as product technical drawings, product modifications, and product bill of material (BOM) are uploaded on the Ingersoll Rand international PLM software. From here, any Ingersoll Rand plant around the world can download and then upload the Bill Of Material of each product on the plant-specific management IT system. Each BOM is identified by a code (ex. AAA, or BBB, or CCC). This code is referred to as *Codice Padre*, being the root code of the final product and from which, the codes of the sub-components generate. The BOM in the international PLM software is structured in the following way:

- Main sub-assembly: sub-products that will then be assembled to make the final product but that are made from sub-pieces. This type of item is referred to as a Make-item, meaning that it is not bought but it is made inside the plant.
- Pieces: components that are bought and used for assembling sub-products. Therefore, they are referred to as Buy-items.

In the BOM structure, each sub-assembly is followed by the list of pieces needed to assemble it.

When the BOM is uploaded to the plant-specific management IT system, it changes structure:

- Sub-assemblies are codified with a ‘0’
- Pieces are codified with a ‘2’.

When an order is received, a work order is created. The work order lists only the items coded with ‘2’. In this way, all the items listed in the work order get reserved for the production of that order. Then, the warehouse prints the list, picks the items, and prepares the kit to assemble the machine. Some of the 2-coded items are small pieces that are managed by Kanban boxes in the warehouse. Those items are not listed in the work order.

Going back to the initial question about why pieces may not be in the BOM or may not be reserved. The answer is that when the Engineering department modifies components in the BOM, these changes are automatically transmitted to the BOM in the plant-specific management system, but not to the work order. Therefore, if a new component is selected for a compressor, that component is not listed in the work order and consequently, it is not picked by the warehouse. Most of the time, those new components are not available in the warehouse. Therefore, if they are not listed in the work order, the warehouse cannot even order them, meaning that when the production discovers that that component is needed, it will have to wait days or weeks to receive it.

In the following picture, the described situation is summarized:

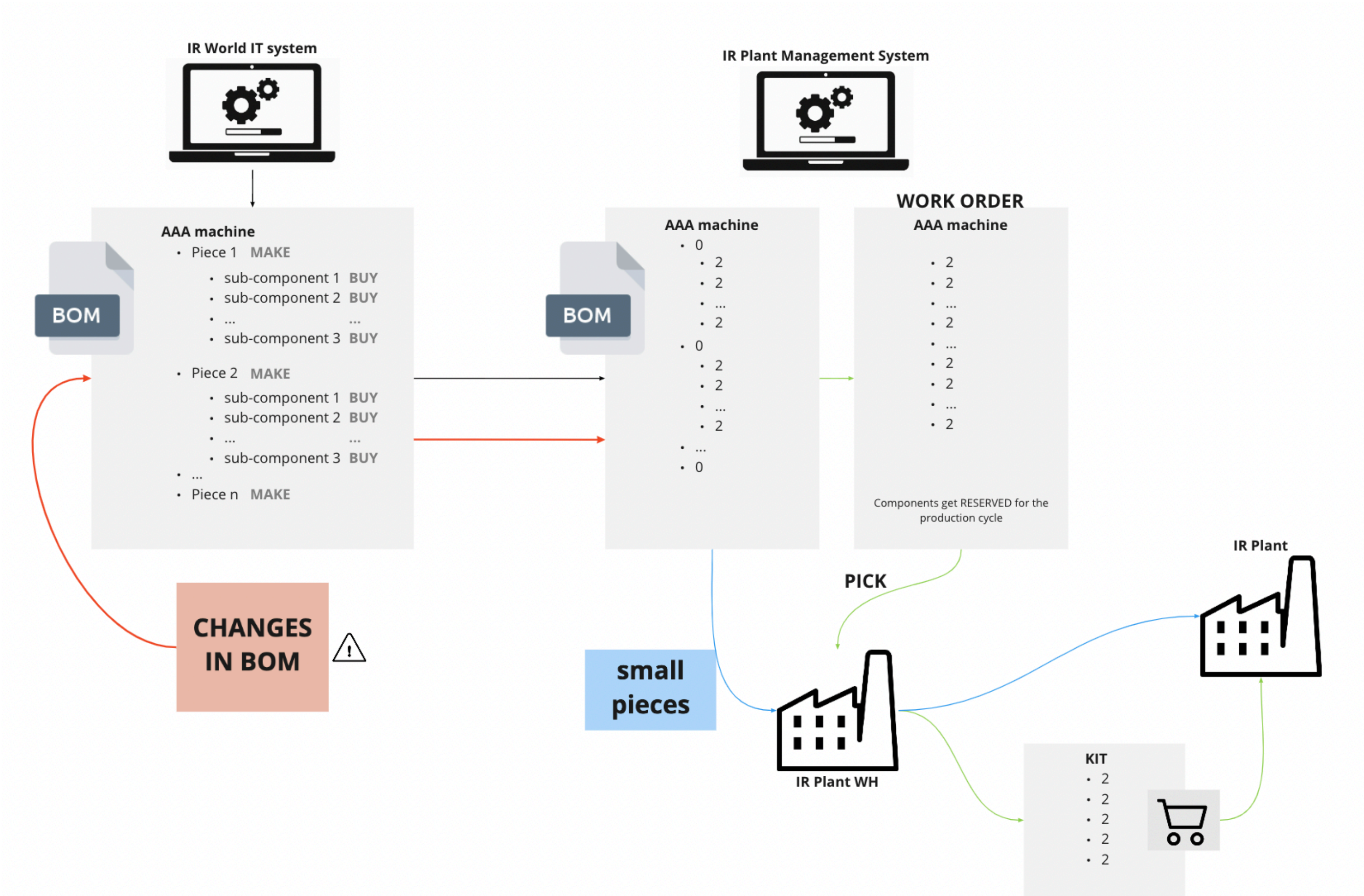


Figure 29: IR Management System Functioning

The last reason why the operator looked for pieces is that the provided pieces had a different identification code from the one mentioned in the procedure. Therefore, the operator had to inform the office to investigate whether the provided component was the correct one. The reason why the pieces had two different codes is that the procedure is old and new components were chosen by the Engineering department without updating the procedure and without informing the production department by a management system notification.

8 Countermeasures Development

Once the root causes were discovered and analyzed, it was time to move to the fifth step of the A3 model that is the development of countermeasures, which are supposed to remove those root causes.
Therefore, starting from each root cause or group of linked root causes, 7 countermeasures were developed, and they are presented in the following paragraphs.

1) TRAINING AND LEARNING BY DOING

   The first root cause presented in the previous chapter is *Unexperienced workers*. Looking back at the data collection and analysis performed on the 29th of April and the 10th of May, 21% of the effective assembly time was spent on understanding the procedure. As already specified this activity was due to the unclearness of the procedure and of the drawings. However, it is evident how the inexperience of workers facilitated the enlarging of this time span. Indeed, if the assembly of rotary compressors was known by operators, they would have already faced those difficulties in understanding the procedure and they would know how to assemble. While they spent more time assembling every single operation than if they had some experience on it. Therefore, it was crucial to act to remove the inexperience of workers.

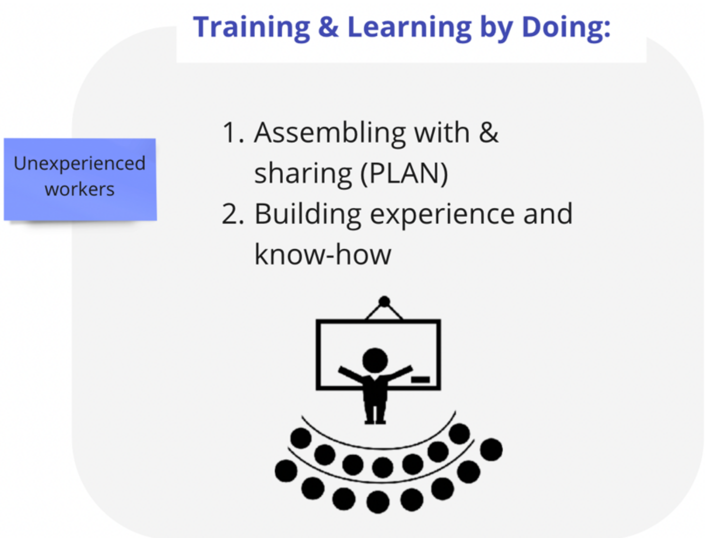


Figure 30: Countermeasure representation in the A3

The countermeasure developed to remove the inexperience of workers proposes two activities:

- Assembling with and Sharing
  The objective was to build a training plan consisting in creating a class of 5 operators that in turn should assemble a rotary compressor with the help of the operator that performed the pilot test. A dedicated rotary unit will. Be used to train new operators. Indeed, the pilot-test operator had the chance to face the possible issues with the assembly or the procedure before any other and to learn how to perform the assembly in the best way. That's why this make of him the best trainer for the 5 operators that will be assigned to the assembly line. The 5 operators will have the chance to learn from the pilot-test operator and listen to him sharing advice. This will be crucial in drastically reducing the time required for the assembly and decrease the probability of making mistakes during the assembly and the consequent reworks.
- Building experience and know-how
  As the time will pass by and the number of rotary compressors assembled will increase, operators will be able to build, secure and stabilize their know-how and experience about the topic, reducing the time required for the assembly and potentially bring to zero the time needed to read and understand the procedure.

2) CUSTOMIZED PROCEDURE

As it comes to the Czech procedure used in the pilot test, many issues arose. The unclearness of the procedure and of the drawings reported in the procedure led the operator to mistakes in the assembly that caused long reworks that wasted 7 hours during the pilot test. Therefore, it was clear from the beginning of the project that the procedure should undergo revision. It was chosen to develop a customized procedure that starting from the Czech one would be modified to fit the needs and desires of the operators and the Vignate plant.

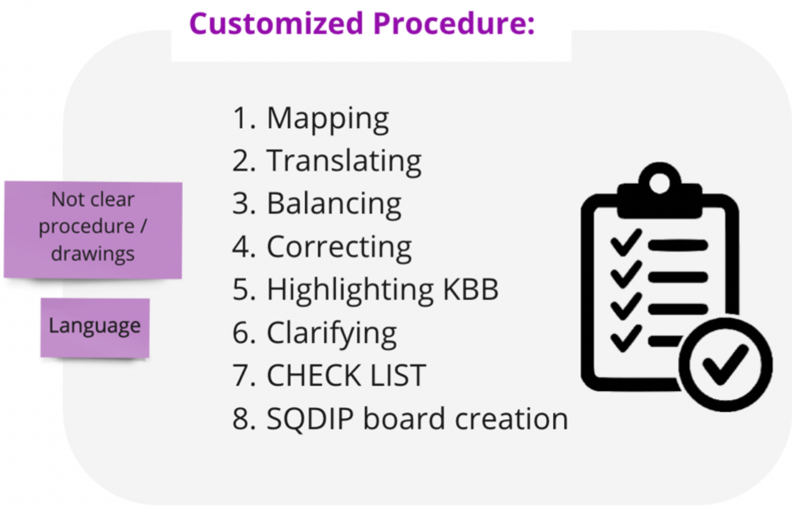


Figure 31: Countermeasure representation in the A3

The development of the customized procedure started by closely observing the operator during the pilot test and by mapping all the required tools, all the components used for the assembly, and all the performed operations of assembly. Then, two lists on Excel were created:

- The list of used components divided by station and operation in which they were needed, highlighting for each of them the required quantity and if they are managed by Kanban boxes in the warehouse. This was crucial to create the new procedure. Indeed, in the new procedure each operation lists the components needed in that operation and reports the description of the item, the quantity, and if they are managed by kanban boxes (KBB).

- The list of required tools divided by station and operation. This list was useful for both the procedure, which highlights which tools to use in each operation, and for the production office to order and buy the tools.

The second step of the development of the customized procedure, was the translation of the description of each operation into the Italian language.

Then, the structure of the procedure underwent a critical analysis that led to:

- The elimination of unnecessary operations. The Czech procedure contains a set of operations that are optional. The choice was to eliminate those operations from the main procedure and leave them as attachments. Indeed, the production plan for rotary compressors includes only the standard type of the product. Therefore, those optional operations will not be needed for sure in the following years.
- The addition of missing operations. Some operations were given for granted and this caused trouble to the operator who had never faced the assembly of the rotary compressor and could not know what to do. Therefore, all those operations were created for the new procedure.
- The balancing of the number of operations in each station. From the pilot test it was evident how station S1 and station S2 were far longer than the other three. Therefore, the order of operations was modified to move some operations from the longest stations to the shortest ones. In the following picture, an example of the moving of the operations is presented:

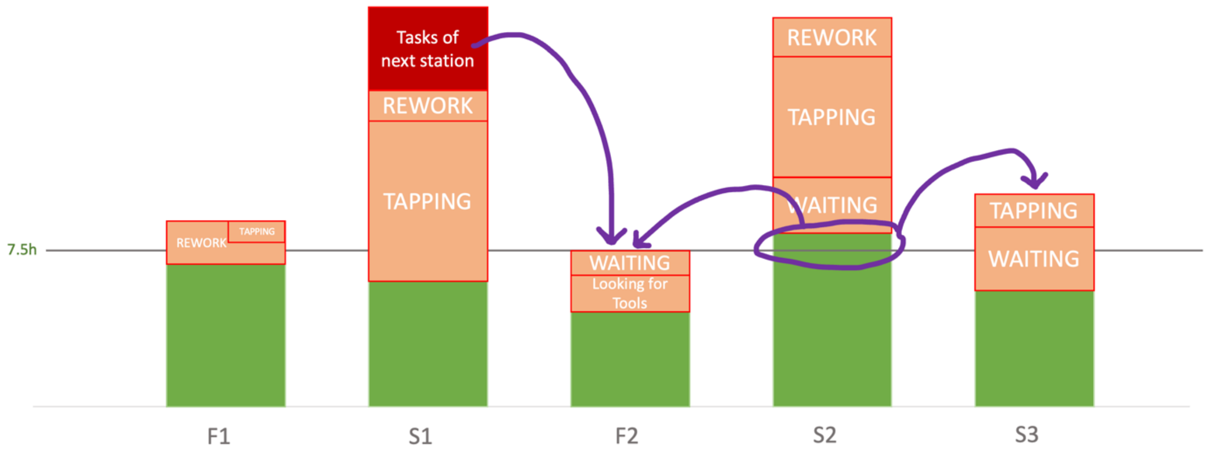


Figure 32: Example of operations Moving

Next step consisted in correcting the procedure from errors and updating it with the changed codes of components.

As already mentioned, components that are managed by Kanban boxes in the warehouse were highlighted in the procedure to help the operator in the supply of material.

Then, it was time to clarify both the procedure and the drawings in the procedure to facilitate the operator's understanding.

Following, the creation of a checklist of critical steps during the assembly was performed. Throughout the pilot test, many critical steps were discovered, and it was chosen to highlight them to avoid errors and decrease the probability of reworks.

Lastly, an SQDIP board was developed to monitor the performance of the assembly line, once it will be implemented and working at full speed and capacity. The parameters that will be periodically reported on the board and monitored are related to 5 classes of topics:

- Safety: measured through the number of near misses.
- Quality: measured through the number of NCM, which are the documents filled anytime a non-conform material or component or activity is discovered.
- Delivery: evaluated by asking if each station was concluded within 7.5 hours.
- Inventory: measured through the number of missing pieces.

- Productivity: measured through the ratio between standard hours on actual hours of Assembly.

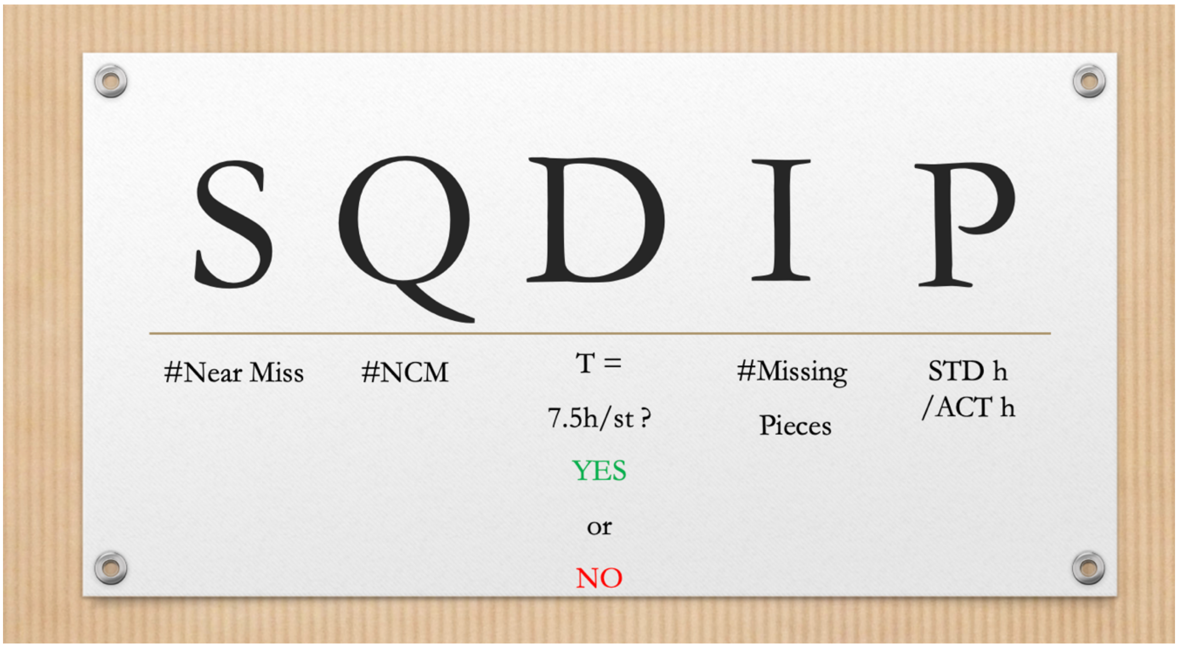


Figure 33: Example of the developed SQDIP Board

3) ADJUSTING LINE LAYOUT

During the pilot test, the current layout appeared inefficient for many reasons already explained. Therefore, one important developed countermeasure consisted in adjusting the line layout. The first step consisted in cleaning the area from anything that is not related to the rotary compressors. As already stated, the area hosted shelves and tables with components that are not used in the rotary assembly. Therefore, they had to be removed.

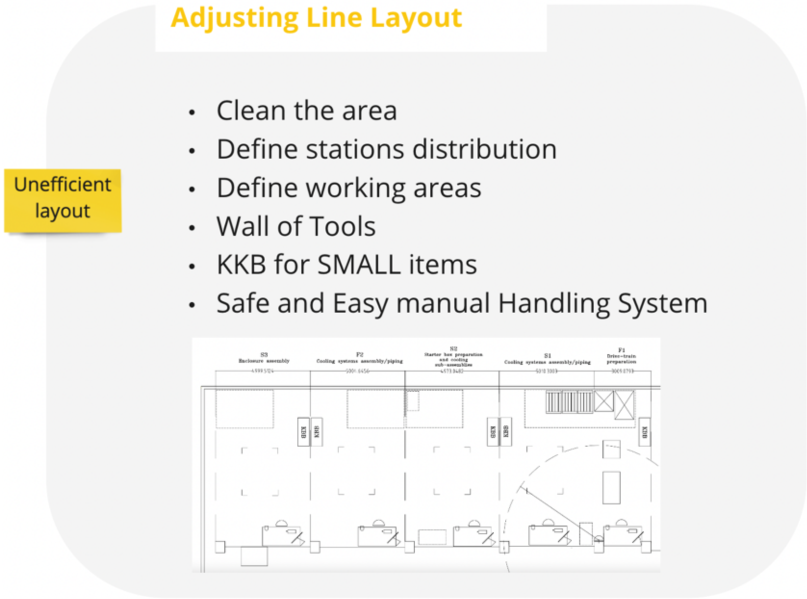


Figure 34: Countermeasure representation in the A3

Then, following the definition of the final station distribution, the area for each station was outlined and identified. The plan was to visually separate and highlight the station, using masking tape on the floor and attaching a sign on the wall with the number of the station to identify each station.

Next, following the emptying of the area, the walls were dedicated to host all the tools required in each station.

In addition, it was chosen that small items managed by Kanban boxes should be on the line so that they are directly available when needed and easing the process of supply of material from the warehouse. In this way the warehouse is only responsible for the other components, while the small ones are always available on the line and picked directly from the operator. Lastly, the handling system topic was tackled. The compressors that are assembled through the line are huge and heavy, therefore a safe handling system is needed. The solution selected a type of manual handling systems, already available in the plant, easily performable by one operator only by a rolling cart. In this way the movement is easy, fast, and totally safe.

4) WALL OF TOOLS

To reduce the time spent by the operator in moving towards the other departments to get the required tools, a wall of tools was created.

Figure 35: Countermeasure representation in the A3

The idea was to create for each station a magnetic structure on the wall where all the needed tools are stored. Thus, the operator has all the necessary tools right on the line avoiding any movements outside the line area in search of them.

5) CLEAN CART

In order to reduce the time spent by the operator in looking for tools, the operator's personal cart must be kept tidy and empty.

Figure 36: Countermeasure representation in the A3

The cart must be used only for:

- holding the procedure to read it,
- hosting the small items needed in the operation that is being executed, such as screws to avoid their falling on the floor and getting lost get lost,
- and storing the tool required in the operation that is being executed.

6) SELF-TAPPING SCREWS

During the pilot test 17 hours were spent in tapping components. It is clear how a solution to this must be proposed. We already know that components come painted from the suppliers and the holes that host the screw get covered in paint losing their tapping capability. The screws proposed by the technical drawings and the BOM are non-self-tapping. Therefore, the operator had to tap all the holes of the components to avoid the breakage of the screw. All the components that needed tapping were mapped during the pilot test.

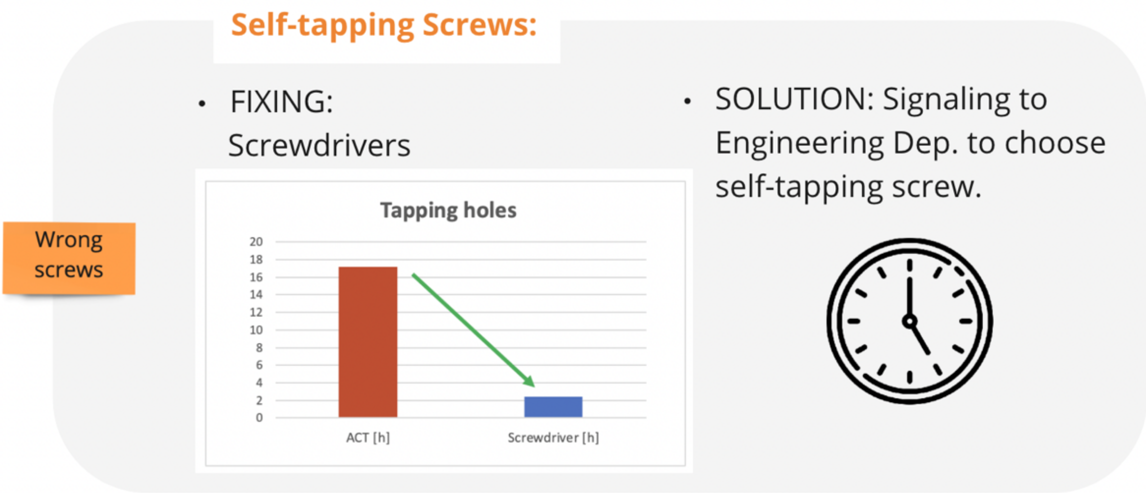


Figure 37: Countermeasure representation in the A3

The long-term solution consisted in signaling to the Engineering Department the need to substitute the AS-IS screws with self-tapping ones, and consequently modifying technical drawings and BOM. It is obvious that this solution will take time to be applied. Therefore, a fixing temporary solution has also been proposed to drastically reduce the time spent tapping. The proposal was to use screwdrivers to tap holes.

Indeed, during the weeks following the pilot test, the screwdriver potentiality was tested. The operator tapped the holes of all the 27 components that need to be tapped using the screwdriver and the relative required time was registered. The results showed that the operator only spent 2.4 hours in tapping. Compared to the 17 hours spent in manually tapping during the pilot test, screwdriver reduces wasted time by 86%.

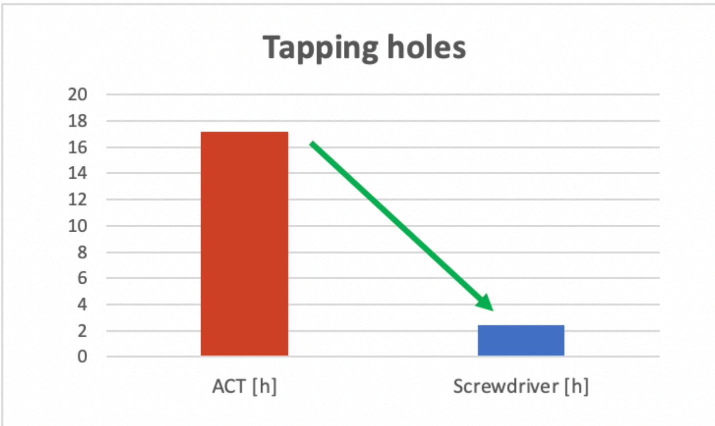


Figure 38: Comparison between Manual Tapping and Screwdriver

7) UPDATING MANAGEMENT SYSTEM

The last proposed countermeasure consists in updating the BOM on the management system to remove the following root causes:

- Not updated system
- Pieces not in BOM
- Pieces not reserved.

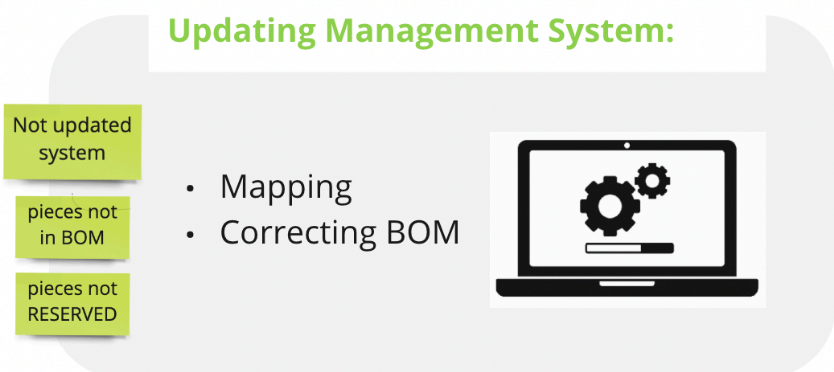


Figure 39: Countermeasure representation in the A3

As already mentioned, during the pilot test all the components needed and used were mapped and listed. This list was crucial to update the BOM in the management system.

IMPACT VS. EFFORT VS. PRIORITY OF THE COUNTERMEASURES

For each countermeasure the impact, the effort and the priority have been evaluated and they are summarized in the following picture:

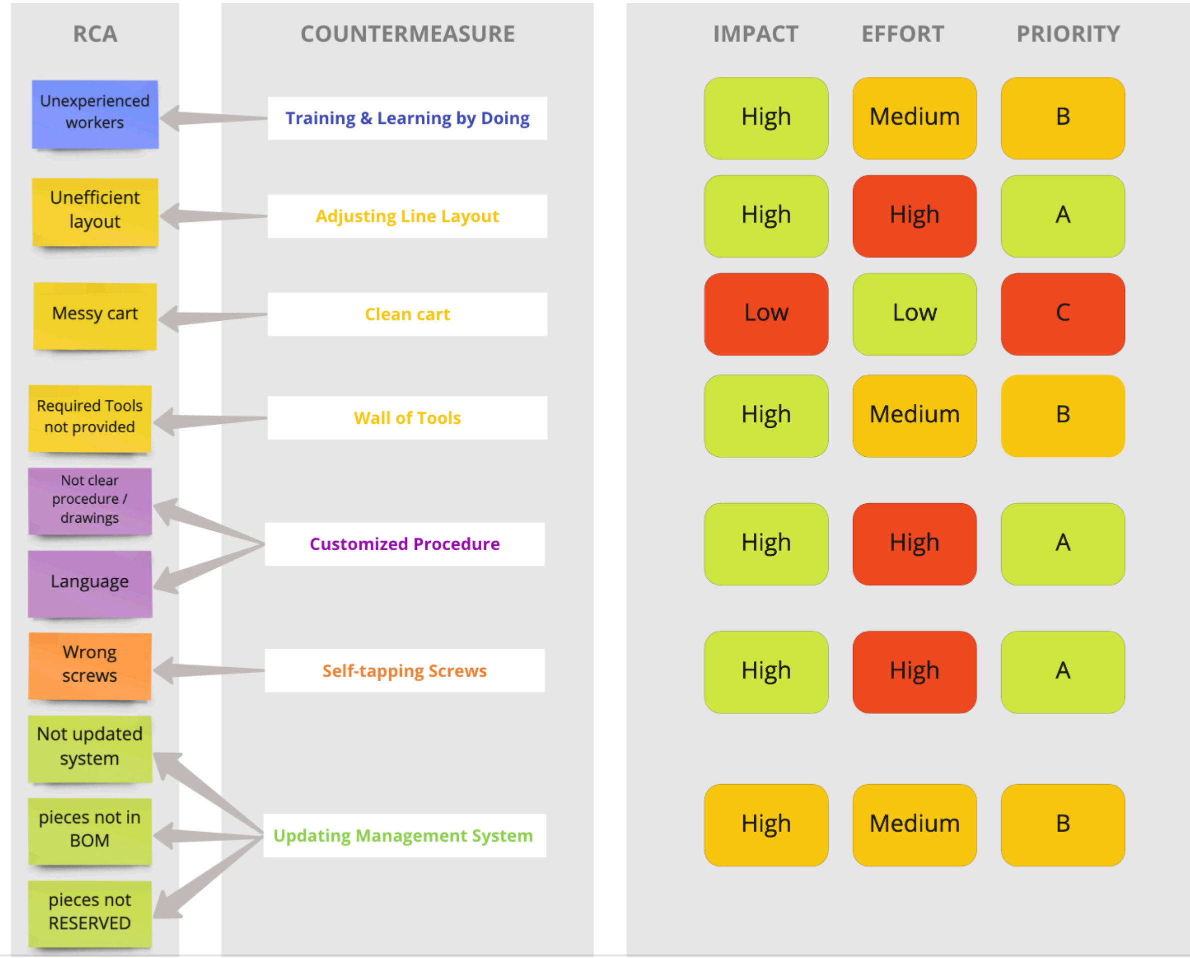


Figure 40: Impact, Effort and Priority of CMs

Starting from the first countermeasure, which is *Training & Learning by Doing*, it can be stated that the impact is high. Indeed, this countermeasure tackles both the time needed to perform assembly operations and the time needed to read and understand the procedure. As regards the effort, this countermeasure requires the definition and schedule of a plan of training for the operators. Resources and time windows must be defined. Therefore, the effort is medium.

Moving on to *Adjusting Line Layout*, this countermeasure both has a high impact and requires a high effort. In addition, it is characterized by a high priority.

As regards the *Clean Cart*, the impact is low since it avoids tools from getting lost but does not act on the main portion of wasted time which was spent in moving towards other departments for tools. At the same time, the effort is very low.

The *Wall of Tools* should bring to zero the movements towards other departments in search of required tools, drastically reducing the time spent looking for tools. The effort, in this case, is medium, since a cost should be sustained by the company to buy all the required tools, but it is a marginal cost with respect to the value of the final product.

	Tools & equipment Cost
F1	135,12 €
S1	151,20 €
F2	389,62 €
S2	71,89 €
S3	167,28 €
Tot.	915,11 €

Figure 41: Cost of Tools

As regards the *Customized Procedure*, both the impact and the effort are high. Indeed, the customized procedure acts on reducing the time spent in understanding the procedure, balances the durations of each station, reduces the bottleneck, and corrects errors that could put the operators in difficulty. At the same time, the workload to create the customized procedure was very high and took a lot of time. This countermeasure has a high priority for the company as it is a crucial topic for the optimization of the assembly line.

Moving on to the *Self-tapping Screws* long-term solution, the impact is high, since it avoids any tapping activity that in the pilot test took 17 hours. However, the effort is high as well since it will take time, further analysis from the Engineering Department, and many modifications to finally take place. The priority is high. That's why an immediate fixing solution has been proposed: the screwdriver.

Lastly, *Updating Management System* has a high impact acting on the missing components and the time spent in looking for components, and a medium effort is required.

9 Countermeasures Implementation

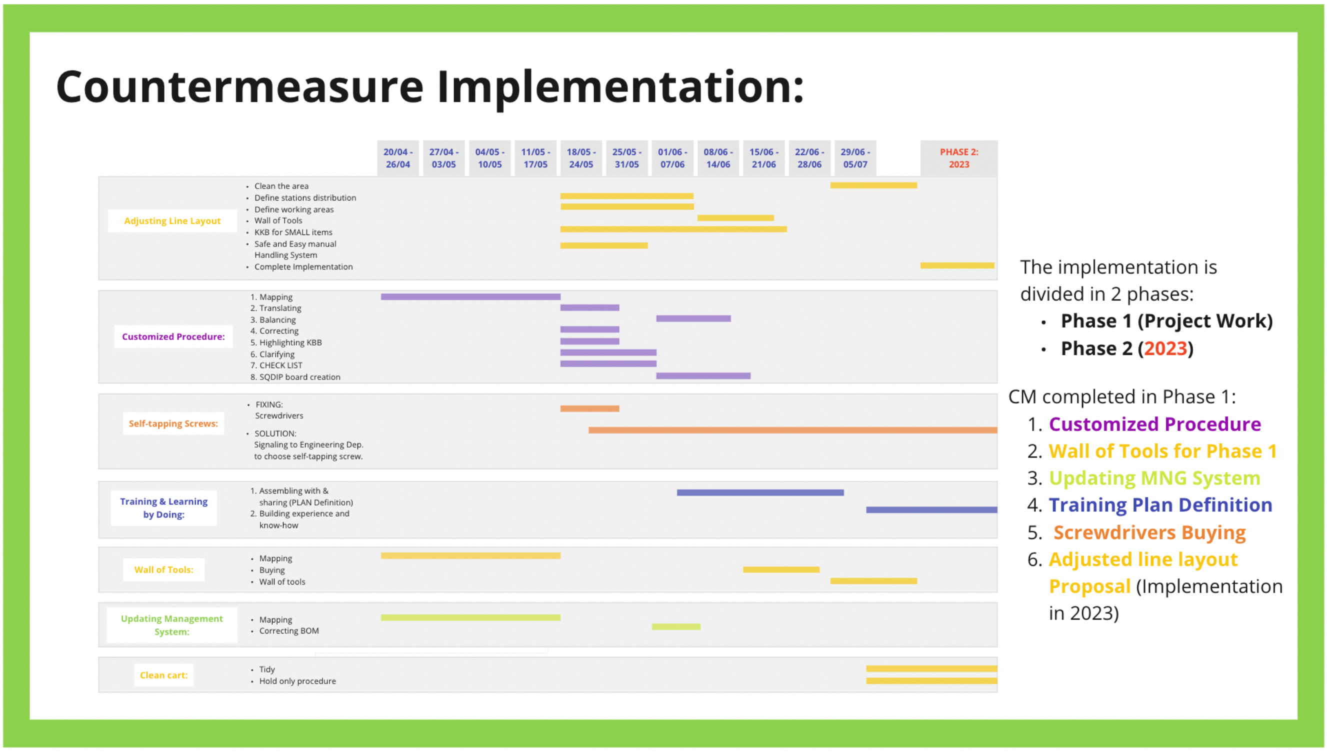


Figure 42: Countermeasure Implementation Box extracted from the A3

Once the countermeasures were proposed, the next step was to implement them.

It must be stated that the effort required to implement an assembly line from zero cannot be concluded in three months, that is the project work duration. It surely requires some intrinsic time due to technicalities and management activities: preparation, investments, gathering of resources and changes in the material management need time to take place. Therefore, the implementation phase has been divided in two phases:

- Phase 1 refers to the project work time window. The phase 1 is expected to define and stabilize the concept of the final assembly line. Indeed, in this phase the assembly line is designed and prepared, but it will not be implemented completely due to the lack of resources. During phase 1, only 2 or 3 operators will be available to work simultaneously on the line. Therefore, the phase 1 implementation cannot be referred to as a real line. However, it will be a crucial phase for testing the efficacy of the proposed countermeasures, of the designed line layout and of the customized procedure.

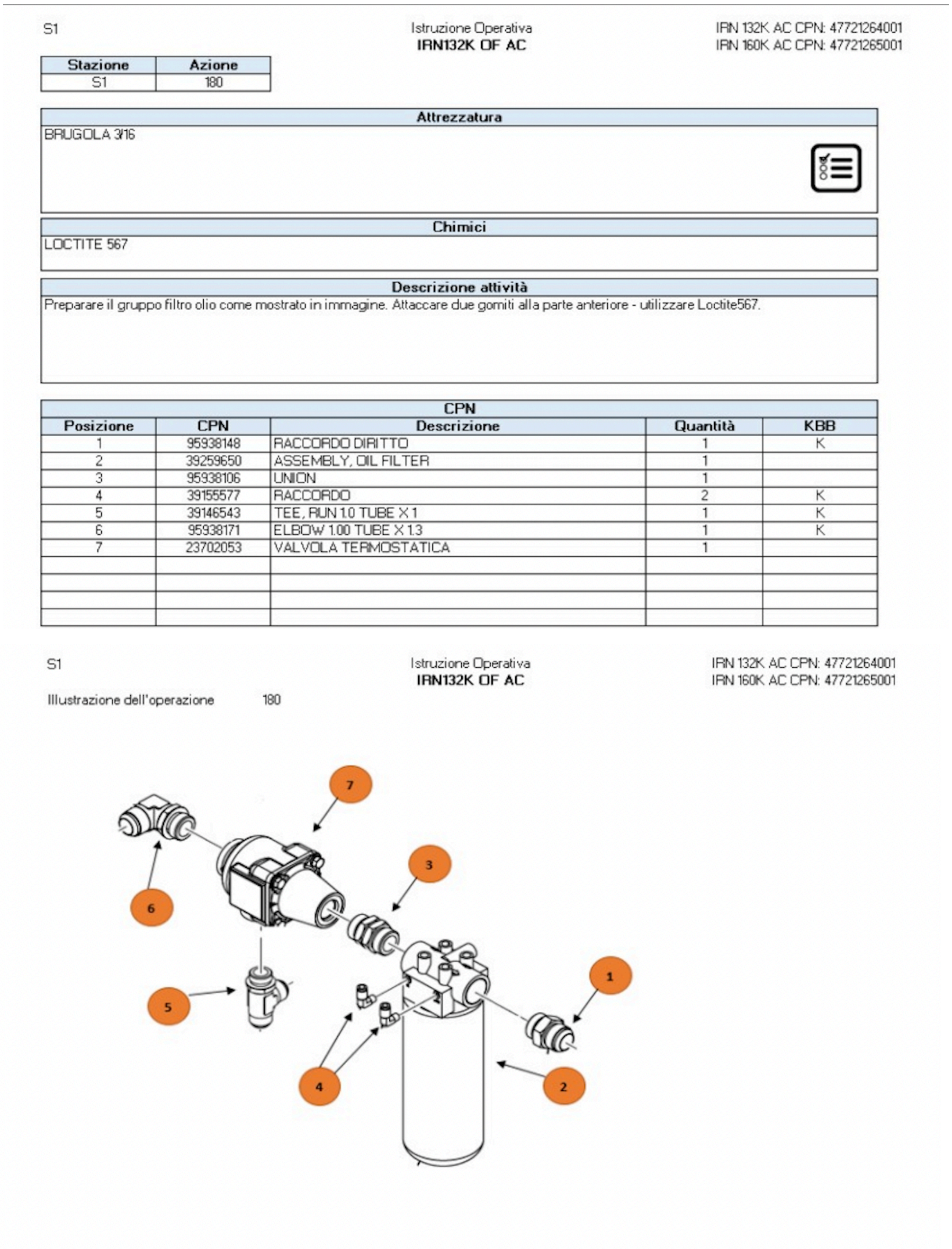
- Phase 2 refers to the final and complete implementation of the assembly line that will be concluded in 2023. In 2023, 5 operators will be enrolled to work on the line, an operator on each station, and the line will work continuously at a pace of a unit assembled every day. Furthermore, the material will be continuously available to the line thanks to the warehouse that will constantly feed with components the stations.

Phase 1 foresaw the implementation of some countermeasures that are listed and described in the following lines:

- The implementation of the *Customized Procedure* started with the mapping of used components, required tools, and performed assembly operations, which lasted almost a month as the duration of the pilot test, starting from the 21st of April. Once concluded the pilot test and consequently also the mapping, the writing of the new customized procedure started and consisted in the translation from Czech to the Italian language, the correction, and the highlighting of small components (managed to KBB) and took about 10 days. At the same time, the procedure was made clear by adding useful drawings and pictures and a checklist for the critical steps was created. These two activities required some more days. Once the procedure was ready, the stations balancing was performed, consisting in moving operations from one station to another to level the duration of each station that appeared very different from one another during the pilot test. This activity lasted 10 days. At the end of the balancing, a total of 31 operations were moved from one station to another. To be precise:
    1. 5 operations were moved from F2 to S1. These are the ones that were unexpectedly anticipated during the execution of S1 in the pilot test. Indeed, these operations regard groups of components that are needed in S1 but are pre-assembled in F2 in the Czech procedure. Anticipating them directly in S1 allows the assembly to follow the proper order of execution of operations.
    2. 11 operations were moved from S1 to F2 to reduce the duration of S1 which was longest in operations if compared to F1, F2 and S3.
    3. 4 operations were moved from F2 to S2. As for S1, S2 recalls for groups of components pre-assembled in F2. Postponing them directly in S2 allows the assembly to follow the proper order of execution of operations.
    4. 6 operations were moved from S2 and S3 to reduce the duration of S2 which was longest in operations if compared to F1, F2, and S3, as station S1.

5. 5 operations were moved from S3 to the other stations. These operations require applying some stickers on the machine. Since during the pilot test the operator faced some difficulties in reaching the internal spots of the machine, once it was completed, it was suggested to apply those stickers directly in the operation that assemble the component that needs the sticker.

Here, an extract from the new procedure is reported:



S1 | Istruzione Operativa **IRN132K OF AC** | IRN 132K AC CPN: 47721264001 IRN 160K AC CPN: 47721265001

Stazione	Azione
S1	180

Attrezzatura

BRUGOLA 3/16

Chimici

LOCTITE 567

Descrizione attività

Preparare il gruppo filtro olio come mostrato in immagine. Attaccare due gomiti alla parte anteriore - utilizzare Loctite567.

CPN				
Posizione	**CPN**	**Descrizione**	**Quantità**	**KBB**
1	95938148	RACCORDO DIRITTO	1	K
2	39259650	ASSEMBLY, OIL FILTER	1	
3	95938106	UNION	1	
4	39155577	RACCORDO	2	K
5	39146543	TEE, RUN 1.0 TUBE X 1	1	K
6	95938171	ELBOW 1.00 TUBE X 1.3	1	K
7	23702053	VALVOLA TERMOSTATICA	1	

S1 | Istruzione Operativa **IRN132K OF AC** | IRN 132K AC CPN: 47721264001 IRN 160K AC CPN: 47721265001

Illustrazione dell'operazione 180

Figure 43: An example of operation in the new procedure

- The *Adjusting* of the *Line Layout* started at the end of the pilot test with the definition of the distribution of the stations and the working areas that were implemented at the beginning of June with masking tape on the floor and signs on the wall. At the same time, the manual handling system tools were applied. Then, the preparation of the wall of tools and the order for dedicated shelves for Kanban boxes were performed. Lastly, once all the required tools arrived, it was time to clean the area from non-rotary elements to be ready for the next planned rotary orders in July. However, as already stated, the final and proper line implementation with one operator per station continuously working will take place in 2023.
- The *Self-tapping Screws* solution started with the mapping of components requiring tapping and signaling them to the Engineering Department, asking to substitute current screws with self-tapping ones. This will require some technical time and it is estimated that will be concluded and ready for phase 2 (2023). The fixing solution proposed the use of screwdrivers that were ordered at the end of the pilot test and were delivered 10 days later.
- The definition of a plan for *Training* consisting in assembling with and sharing key advice was started at the beginning of June and took almost a month as it usually happens when organizing a plan of training for resources. As regards the Building of Experience and Know-how this will be only possible as the number of rotary compressors built will increase. Till the end of June, only one rotary compressor was planned to be assembled and was the one of the pilot tests. The next rotary compressors were planned to be assembled in the month of July.
- The *Wall of Tools* started with the mapping of required tools and then proceeded with the order execution and the preparation of the dedicated wall concluded at the end of June.
- *Updating Management System* started with the mapping of the components that were used during the pilot test assembly. Then, it consisted in changing the BOM in the management system according to the mapped list. This activity was performed at the beginning of June.
- Lastly, operators will be instructed about the *Clean Cart* rules in July, once the assembly of rotary compressors will start again.

In the following figure the Gantt Chart relative to the project activities is represented:

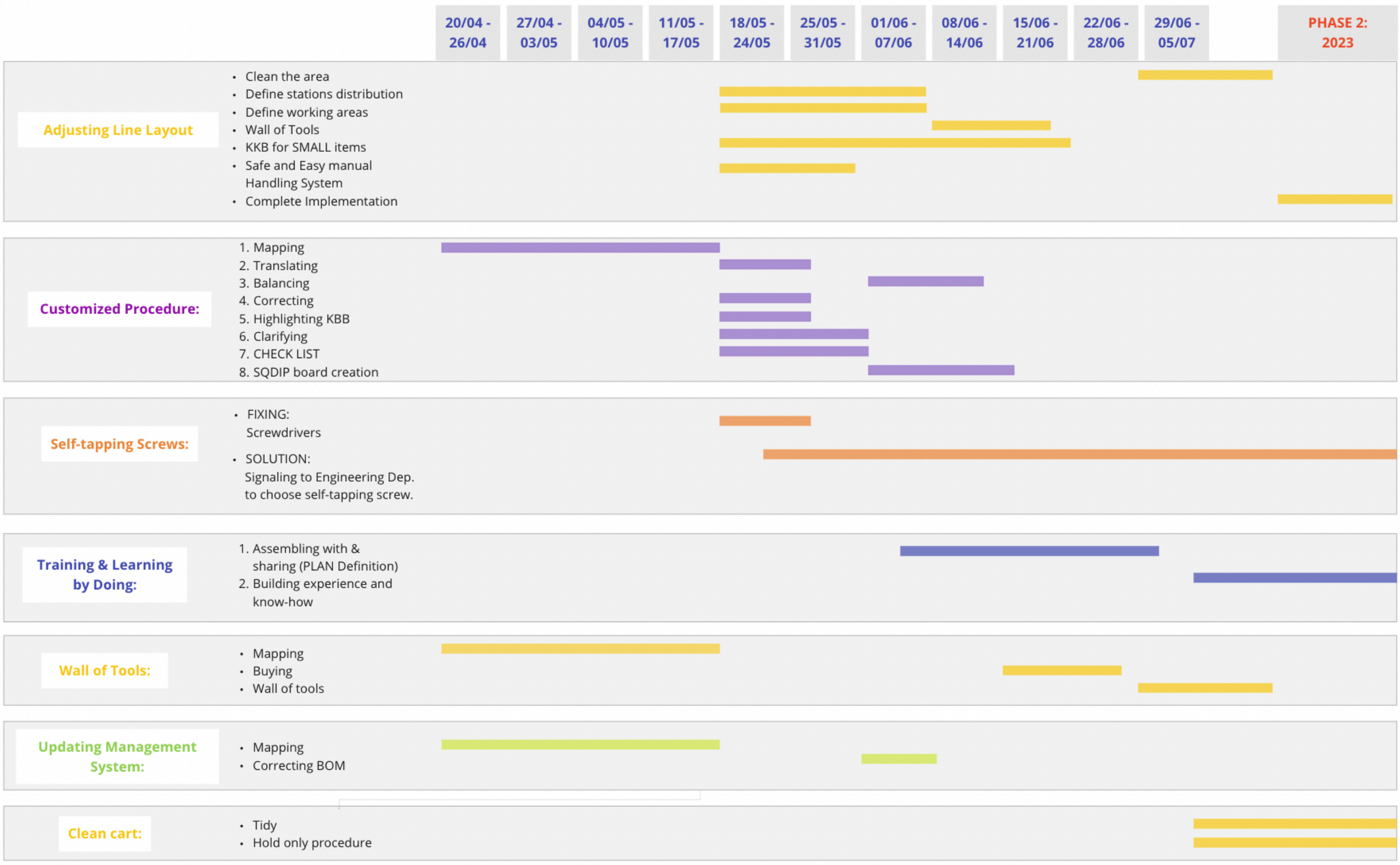
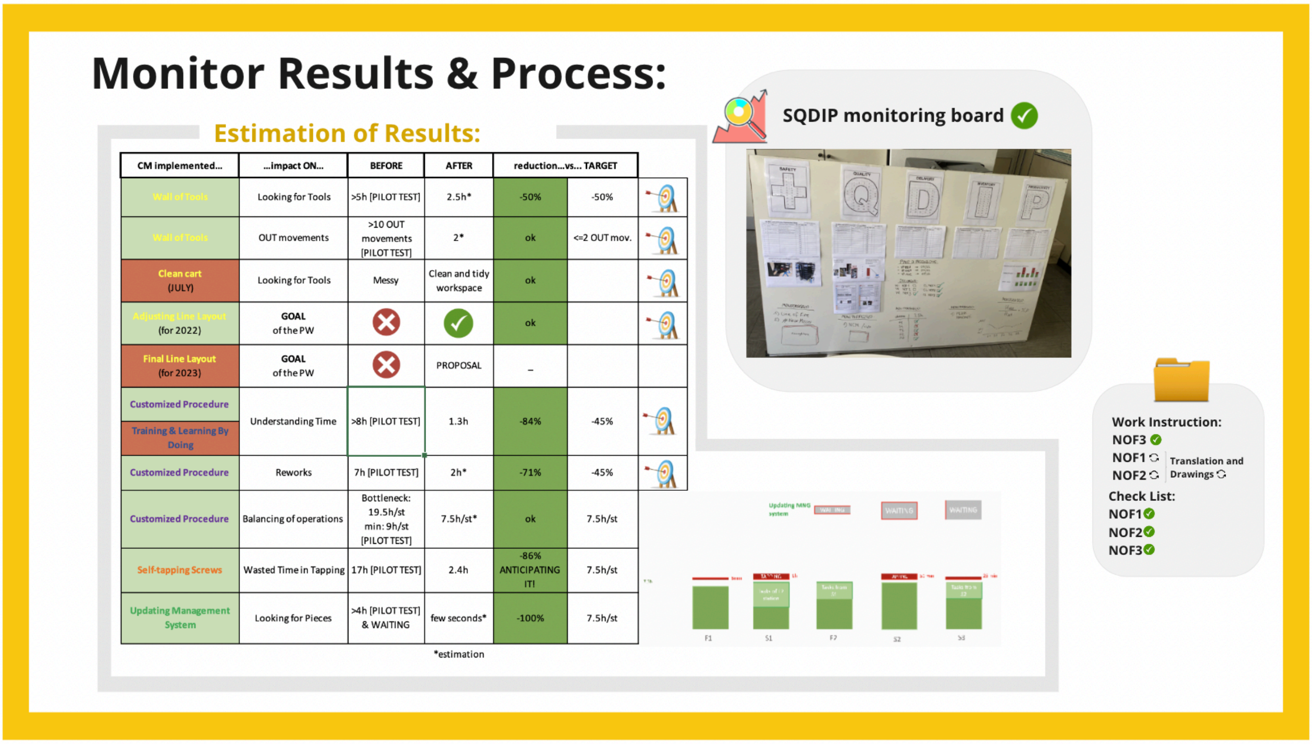


Figure 44: Gantt Chart of the Project

10 Monitor & Control



CM implemented…	…impact ON…	BEFORE	AFTER	reduction…vs… TARGET	
Wall of Tools	Looking for Tools	>5h [PILOT TEST]	2.5h*	-50%	-50%
Wall of Tools	OUT movements	>10 OUT movements [PILOT TEST]	2*	ok	<=2 OUT mov.
Clean cart (JULY)	Looking for Tools	Messy	Clean and tidy workspace	ok	
Adjusting Line Layout (for 2022)	GOAL of the PW	✗	✓	ok	
Final Line Layout (for 2023)	GOAL of the PW	✗	PROPOSAL	–	
Customized Procedure / Training & Learning By Doing	Understanding Time	>8h [PILOT TEST]	1.3h	-84%	-45%
Customized Procedure	Reworks	7h [PILOT TEST]	2h*	-71%	-45%
Customized Procedure	Balancing of operations	Bottleneck: 19.5h/st min: 9h/st [PILOT TEST]	7.5h/st*	ok	7.5h/st
Self-tapping Screws	Wasted Time in Tapping	17h [PILOT TEST]	2.4h	-86% ANTICIPATING IT!	7.5h/st
Updating Management System	Looking for Pieces	>4h [PILOT TEST] & WAITING	few seconds*	-100%	7.5h/st

*estimation

Figure 45: Monitor Box extracted from the A3

As already stated, after the pilot test no other rotary compressors were planned to be assembled before the month of July. Therefore, this master thesis does not include the direct monitoring of results obtained by the countermeasures implementation.

However, an estimation about the impact of each countermeasure is given in the following paragraphs, based on the data collected during the pilot test and performing, when possible, simulations.

WALL OF TOOLS

The *Wall of Tools* is meant to impact on the time spent in looking for tools and the number of movements towards the other departments, exiting the area dedicated to the line.

During the pilot test, more than 5 hours were wasted and more than 10 movements outside the line were made in looking for tools that were not on the line.

Since the *Wall of Tools* collects all the tools that were used during the pilot test, it can be reasonable to expect that the time spent looking for tools will be halved and a maximum of

2 out movements will be required. Therefore, comparing the estimated results with the related set targets, that are:

- the reduction by 50% of looking for tools time, and
- a maximum of 2 out movements accepted,

the *Wall of Tools* is expected to be a successful countermeasure.

CLEAN CART

As regards the *Clean Cart*, this will be implemented in July as soon as the rotary production will start. This will impact the time wasted in looking for tools and will guarantee a tidy and clean workspace.

ADJUSTING LINE LAYOUT

As already stated, the complete and final assembly line will be implemented in 2023. However, to satisfy the planned production for the year 2022 in the best way and the goal of the project to define and optimize the line, the current area dedicated to rotary assembly was adjusted to host a temporary line. We already stated that the one implemented in June is not a proper line, since only 2 or 3 operators will be allowed to work simultaneously but this will surely improve the situation with respect to the pilot test. During the pilot test, the line was just a draft, while at the end of the project the line layout was perfectionated and adjusted, reaching the goal of the project work.

CUSTOMIZED PROCEDURE

The *Customized Procedure* is expected to impact on:

- Understanding time
- Reworks
- Balancing of operations.

To evaluate the impact of the new procedure on the time spent in reading and understanding time, a simulation was performed. The simulation was performed with the help of the same operator of the pilot test to be able to estimate also the impact of *Training & Learning By Doing* on the same understanding time.

The simulation consisted in the operator reading the new procedure and for each operation he would communicate when he was ready to start to assemble, having understood what the operation asked to do. In this way, the understanding time required by the new customized procedure read by an experienced operator (the operator was at his second assembly of the same product) was timed. The operator employed on average 30 seconds to read each operation, resulting in a total of 1.3 hours of understanding time. The understanding time required during the pilot test using the Czech procedure was more than 8 hours. Therefore, the *Customized Procedure* together with the *Training & Learning By Doing* is estimated to reduce the understanding time by 84%, which is higher than the reduction set as a target (-45%).

The Customized Procedure impacts also on the reworks. As it has been already explained, the 7 hours of reworks faced during the pilot test were all traceable back to the unclearness of the procedure and its drawings. The new procedure eliminated that root cause since the unclear drawings and texts of the procedure had been substituted and clarified. Therefore, the reworks needed during the pilot test should not happen again with the new procedure. However, to be safe, it is estimated that 2 hours of reworks could be faced even with the new procedure. Then, the new procedure is estimated to lead to a reduction of 71% of reworks. The targets set a reduction of 45% of the reworks.

Lastly, the *Customized Procedure* impacts on the balancing of operations among stations. During the pilot test it was clear how stations had very different duration: the bottleneck station lasted 19.5 hours while the shortest station took 9 hours. Therefore, the operations were redistributed among stations. The balancing of operations is expected to guarantee that all stations will reach the target duration of 7.5 hours.

Therefore, the *Customized Procedure* is expected to be successful in reaching all the related targets.

SELF-TAPPING SCREW

The implementation of self-tapping screw will not take place before 2023. However, a fixing solution was proposed to reduce the wasted time in tapping: the use of *Screwdrivers*.

During the pilot test 17 hours were spent in tapping holes. After the pilot test, the screwdriver performance was tested and only 2.4 hours were needed to tap the same components. Therefore, the reduction of tapping time allowed using the screwdriver is 86%.

UPDATING MANAGEMENT SYSTEM

During the pilot test the operator wasted more than 4 hours in looking for pieces that had not been provided by the warehouse, because those pieces were not in the BOM or were not *reserved*. Therefore, updating the management system was required using the list of components mapped during the pilot test. In this way the BOM in the system is updated and components can be correctly *reserved*. Of course, we cannot act on the Environment causes such as the Ukrainian and Chinese situation. However, the updating of the management system will avoid the missing of pieces that are due to causes included in the scope of the project (errors in the BOM and in the system). Therefore, we can suppose that the time wasted in looking for pieces will be reduced to just a few seconds, guaranteeing that each station will be concluded within 7.5 hours.

ASSEMBLING WITHIN THE TIME CONSTRAINT

In the following figure, the impact of the last three described countermeasures is summarized and it shows how the time target of 7.5 hours per station is expected to be satisfied.

As already stated, the *Customized Procedure* acted on the balancing of the stations to guarantee that each station is concluded within 7.5 hours. In addition, *Screwdrivers* reduced the time wasted in tapping by 86%. Since, until phase 2, the tapping activity cannot be avoided, it is proposed to execute the tapping activity in advance. In this way, it will not impact the duration of the station, guaranteeing the respect of the 7.5 hours target.

At the same time, *Updating Management System* is expected to reduce to just a few seconds the time spent in looking for pieces and waiting for their arrival.

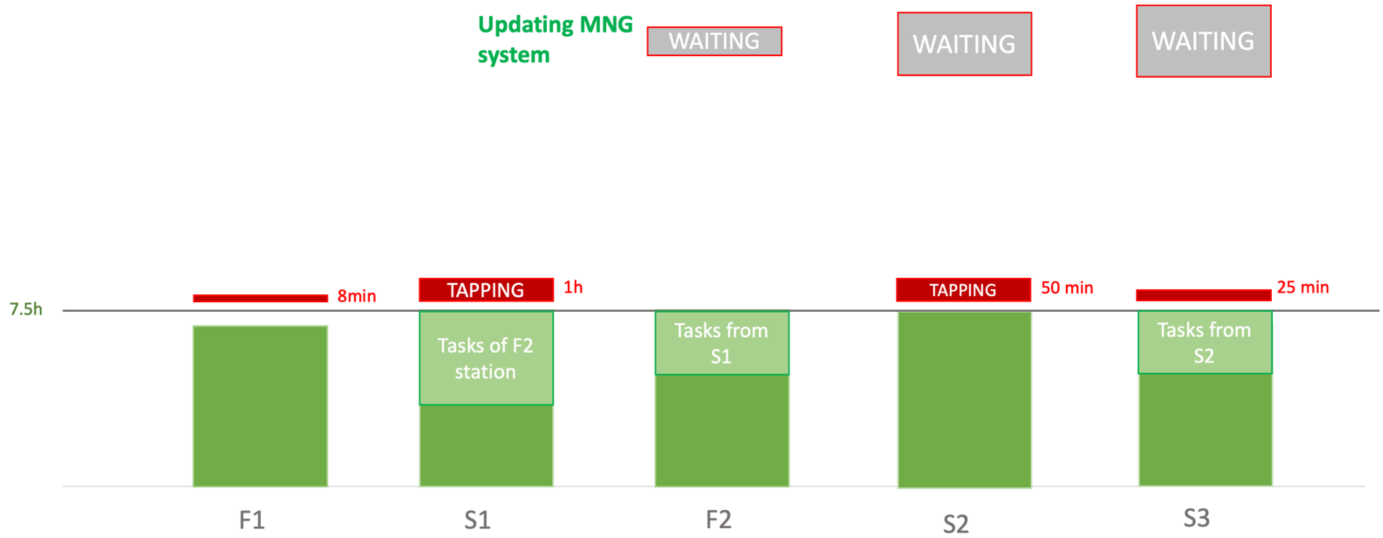


Figure 46: TO BE stations durations

CM implemented...	...impact ON...	BEFORE	AFTER	reduction...vs... TARGET		
Wall of Tools	Looking for Tools	>5h [PILOT TEST]	2.5h*	-50%	-50%	
Wall of Tools	OUT movements	>10 OUT movements [PILOT TEST]	2*	ok	<=2 OUT mov.	
Clean cart (JULY)	Looking for Tools	Messy	Clean and tidy workspace	ok		
Adjusting Line Layout (for 2022)	**GOAL** of the PW	✗	✓	ok		
Final Line Layout (for 2023)	**GOAL** of the PW	✗	PROPOSAL	–		
Customized Procedure Training & Learning By Doing	Understanding Time	>8h [PILOT TEST]	1.3h	-84%	-45%	
Customized Procedure	Reworks	7h [PILOT TEST]	2h*	-71%	-45%	
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Self-tapping Screws	Wasted Time in Tapping	17h [PILOT TEST]	2.4h	-86% ANTICIPATING IT!	7.5h/st	
Updating Management System	Looking for Pieces	>4h [PILOT TEST] & WAITING	few seconds*	-100%	7.5h/st	

*estimation

Table 2: Expected Results vs Target

SQDIP MONITORING BOARD

During the project work, a monitoring tool was developed, the SQDIP monitoring board. In this way, the company will be able to monitor the performance of the line regarding safety, quality, delivery, inventory, and productivity. Data will be written on the SQDIP board in the line and will be evaluated. This will be crucial to continuously improve the assembly line.

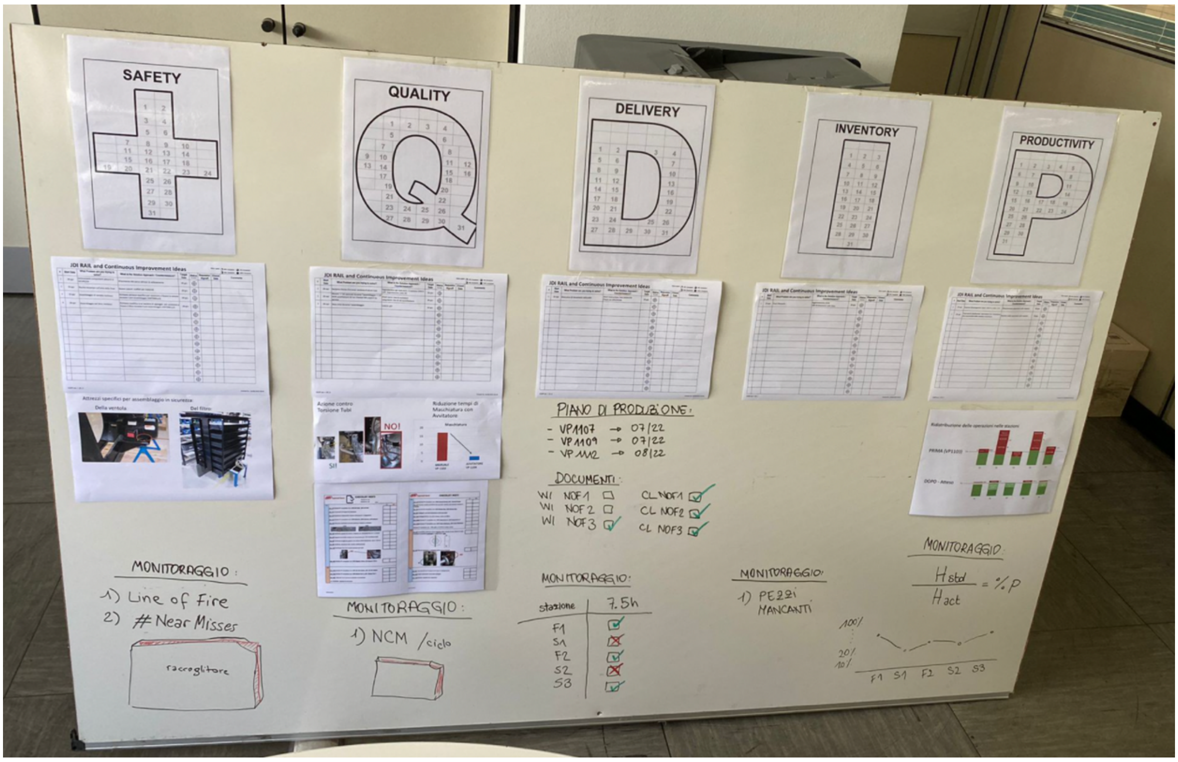

Figure 47: Photo taken to the SQDIP implemented for the project

COLLECTION OF DOCUMENTS

At the beginning of the project work, only a few documents were available in the company for the rotary compressors: the procedures in Czech language for the 3 models of Nirvana rotary compressors.

The project work allowed the company to gain a collection of completely customized documents:

- The NOF 3 procedure and the check list for critical step.
- The check lists for NOF 2 and NOF 1.
- The translation and selection of drawings for the procedures of NOF 2 and NOF 1.

11 Follow Up

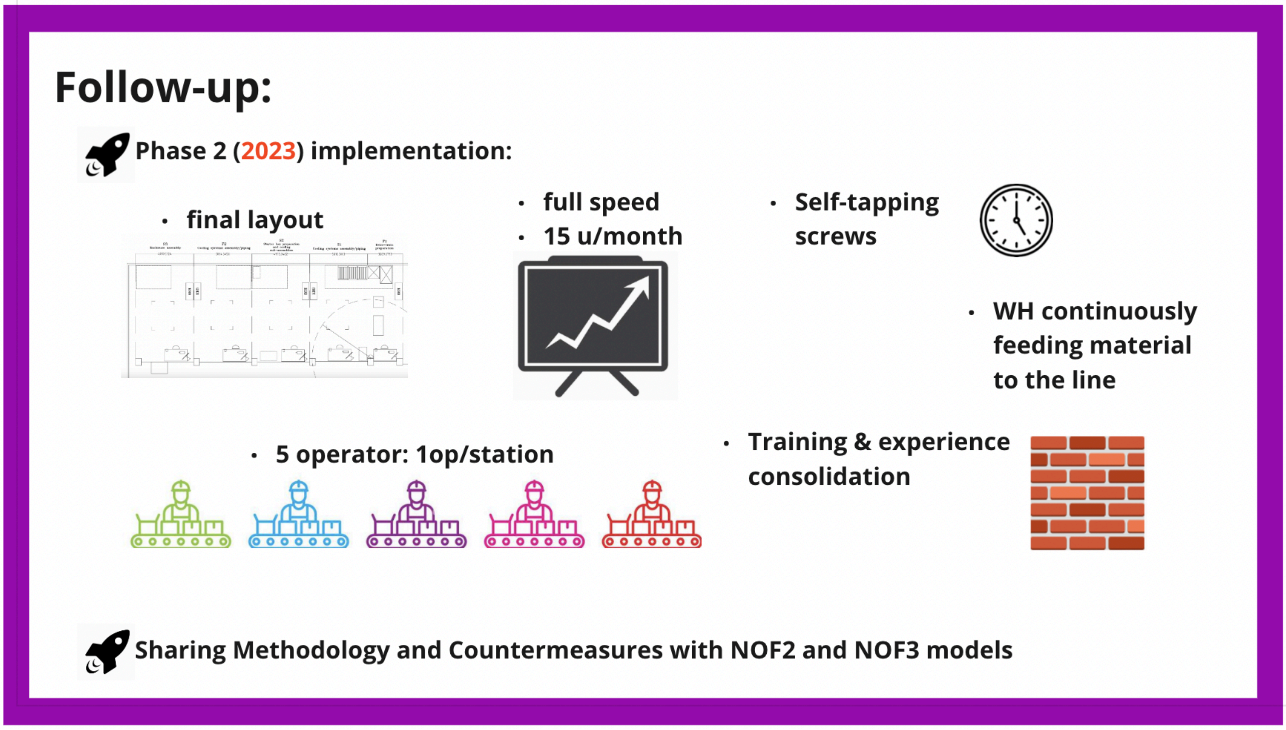

Figure 48: Follow Up Box extracted from the A3

The Follow Up step of the A3 framework refers to what must follow the project work. It is also referred to as Standardize & Share Success. It is meant to list issues left unresolved by the project and promotes the standardization and the sharing of obtained results, consisting in solidifying the knowledge and sharing it throughout the whole organization.

In this case study, some countermeasures remained un-implemented due to their required time that was longer than the one available for the project work. This is the case of the assembly line implementation, that will not take place before 2023. Indeed, during phase 2 the proper assembly line will see the light:

- The final layout will be implemented following the layout proposal delivered during the project.
- Dedicated resources will be enrolled to allow 1 operator in each station, working simultaneously and assembling a unit per day.

- The line will work at full speed reaching the planned production of 15 units per month.
- Furthermore, a clever and efficient way to manage materials will be designed in such a way that the warehouse could continuously feed the stations with required components.
- The higher number of units assembled will allow the plan of training and the experience to consolidate reducing further the assembly time, potentially reaching the nice-to-have target of 4 hours per station as it was in the Czech plant. Furthermore, the substitution of common screws with the self-tapping ones will bring to zero the wasted time due to tapping.

We must specify that this project work analyzed only one model of rotary compressor. It can be interesting and useful to repeat the same activities for the other models of rotary compressors to optimize and improve their assembly and reach the same results as for the analyzed model. Promoting a pilot test during which the mapping of components, tools, and operations could be performed. The list of components will be used to update the management system to avoid the lack of pieces and the related wasted time. The list of tools will be used to compare it to the current list one and to buy those tools not available yet and to add them to the Wall of Tools on the line. Lastly, the notes about operations will be fundamental to complete the already translated customized procedure as done during the project work. In such a way, an optimized and flexible assembly line can be easily created, allowing different types of rotary compressors to continuously flow through the line, increasing production volumes and decreasing the assembly line for each type of rotary compressor.

12 My Experience

"Difficult roads often lead to beautiful destinations"

My experience with IM Lab 2 did not start as planned: the company I was initially assigned to kept delaying my entry week after week. To keep motivation high was hard but thanks to Prof. Portioli and my methodological tutor Eng. Frecassetti' support and efforts, my experience finally started in a new company!

Ingersoll Rand offered me the precious chance to practice in the manufacturing field in a multinational company. The project allowed me to turn into action the great deal of hours of lessons and study. To be part of a team in a real manufacturing industry and operate for a very tangible goal as to implement an assembly line was for me a rare and unique opportunity. I end my experience in Ingersoll Rand enriched both professionally and humanly.

At first the project impressed and worried me a lot but after only a few days I realized that I had been very lucky indeed. The support that I received from anyone at any level was great and sincere. First, a special thank goes to Eng. Francesco Audino, the Manufacturing Leader, for his helpful and constant advice throughout the whole project. A thank goes also to the Package team leader and the operator of the pilot test, Salvatore: their willingness to help me added huge value to the project output.

Last but not least, I must thank Eng. Sara Cremonesi, my company tutor and my guide in the project days. Her sincere support and eagerness to let me learn is something I would be forever grateful for.

Finally, I would like to thank Prof. Alberto Portioli Staudacher and my methodological tutor Eng. Stefano Frecassetti for their steady intervention and continuous encouragement.

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Sitography

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https://mag.toyota.co.uk/heijunka-toyota-production-system/
https://kanbanize.com/continuous-flow/heijunka#:~:text=Heijunka%20is%20a%20Lean%20method%20for%20reducing%20the%20unevenness%20in,in%20the%20best%20possible%20way.
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https://www.lean.org/the-lean-post/articles/5s-is-a-way-of-thinking-and-practice/
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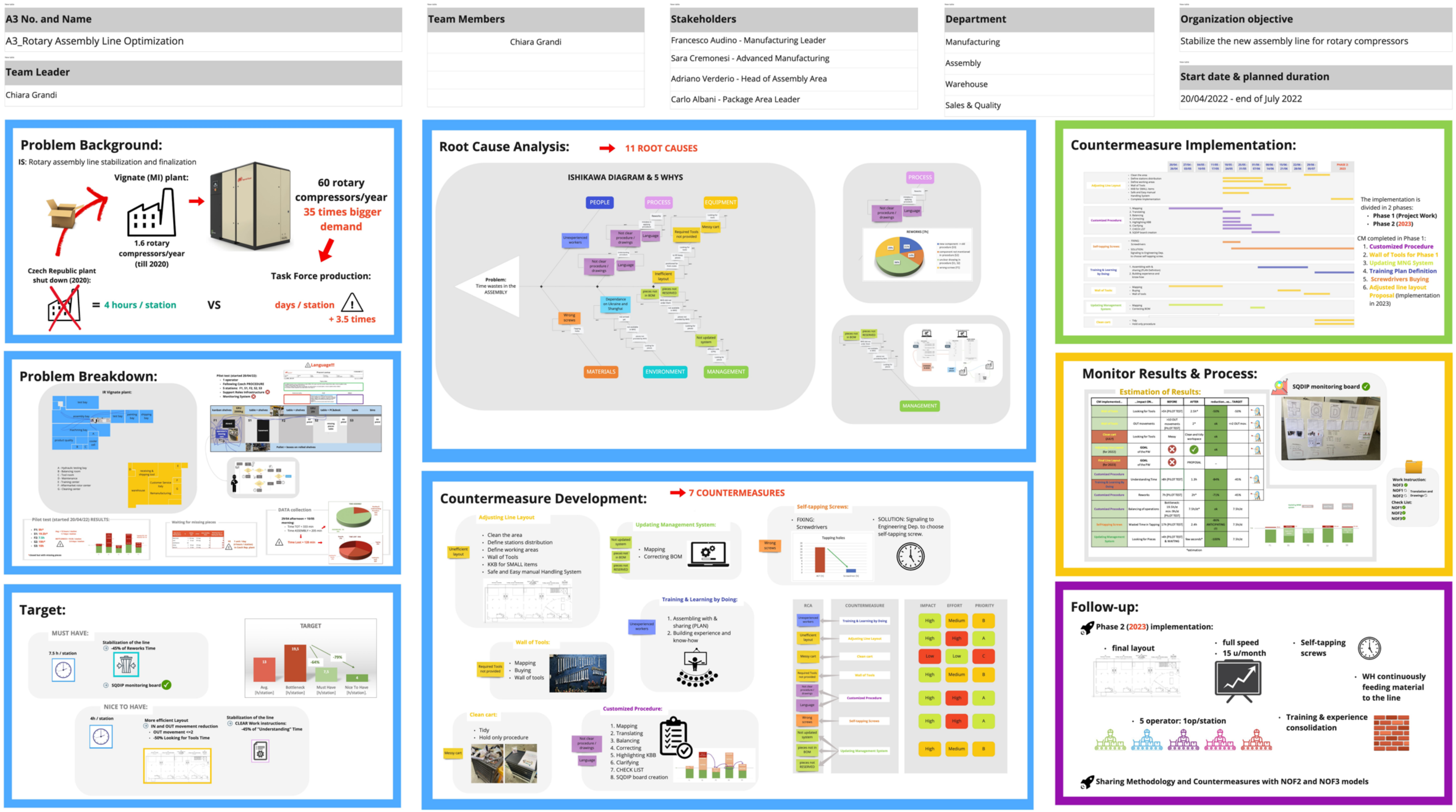
List of Figures

List of Tables

A Attachments

A.1. The A3 framework


A3 No. and Name
A3_Rotary Assembly Line Optimization
Team Leader
Chiara Grandi
Team Members
Chiara Grandi
Stakeholders
Francesco Audino - Manufacturing Leader
Sara Cremonesi - Advanced Manufacturing
Adriano Verderio - Head of Assembly Area
Carlo Albani - Package Area Leader
Department
Manufacturing
Assembly
Warehouse
Sales & Quality
Organization objective
Stabilize the new assembly line for rotary compressors
Start date & planned duration
20/04/2022 - end of July 2022
Problem Background:
IS: Rotary assembly line stabilization and finalization
Vignate (MI) plant:
1.6 rotary compressors/year (till 2020)
60 rotary compressors/year
35 times bigger demand
Czech Republic plant shut down (2020):
= 4 hours / station
VS
Task Force production:
days / station
+ 3.5 times
Problem Breakdown:
Root Cause Analysis:
11 ROOT CAUSES
ISHIKAWA DIAGRAM & 5 WHYS
PEOPLE
PROCESS
EQUIPMENT
MATERIALS
ENVIRONMENT
MANAGEMENT
Problem: Time wastes in the ASSEMBLY
Countermeasure Implementation:
The implementation is divided in 2 phases:
Phase 1 (Project Work)
Phase 2 (2023)
CM completed in Phase 1:
1. Customized Procedure
2. Wall of Tools for Phase 1
3. Updating MNG System
4. Training Plan Definition
5. Screwdrivers Buying
6. Adjusted line layout Proposal (Implementation in 2023)
Monitor Results & Process:
Estimation of Results:
SQDIP monitoring board
Target:
MUST HAVE:
7.5 h / station
Stabilization of the line
-45% of Reworks Time
SQDIP monitoring board
TARGET
NICE TO HAVE:
4h / station
More efficient Layout
IN and OUT movement reduction
OUT movement <=2
-50% Looking for Tools Time
Stabilization of the line
CLEAR Work instructions:
-45% of "Understanding" Time
Countermeasure Development:
7 COUNTERMEASURES
Adjusting Line Layout
Clean the area
Define stations distribution
Define working areas
Wall of Tools
KKB for SMALL items
Safe and Easy manual Handling System
Updating Management System:
Mapping
Correcting BOM
Self-tapping Screws:
FIXING: Screwdrivers
SOLUTION: Signaling to Engineering Dep. to choose self-tapping screw.
Training & Learning by Doing:
1. Assembling with & sharing (PLAN)
2. Building experience and know-how
Wall of Tools:
Mapping
Buying
Wall of tools
Clean cart:
Tidy
Hold only procedure
Customized Procedure:
1. Mapping
2. Translating
3. Balancing
4. Correcting
5. Highlighting KBB
6. Clarifying
7. CHECK LIST
8. SQDIP board creation
RCA
COUNTERMEASURE
IMPACT
EFFORT
PRIORITY
Follow-up:
Phase 2 (2023) implementation:
final layout
full speed
15 u/month
Self-tapping screws
WH continuously feeding material to the line
5 operator: 1op/station
Training & experience consolidation
Sharing Methodology and Countermeasures with NOF2 and NOF3 models

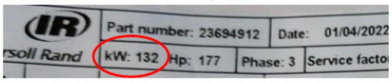
A.2. Check List

CHECKLIST

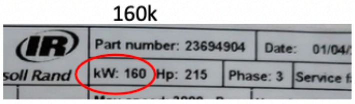
Unit: ____________________

		SI	NO
F1	Op. 10 Scheda PP compilata con: **CPN Air End, S/N Air End**		
	Op. 10 Conservati 23 tappi nel sacchetto		
	Op. 20 Resistenza isolamento motore misurata (> 1 Megaohm)		
	Op. 20 Scheda PP compilata con: **CPN Motore, CPN Statore, S/N Statore**		
	Op. 20 Attaccata etichetta secondo potenza motore e modello:		

132k

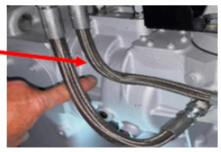


160k



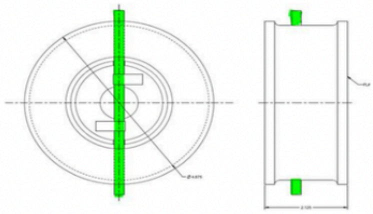
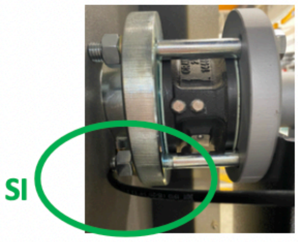
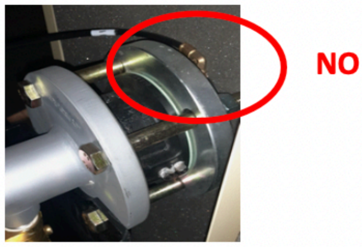
		SI	NO
	Op. 30 Verificato spazio tra rotore e statore con SPESSIMETRO (0,7-1,2mm)		
	Op. 30 Eseguito controllo motore con strumento per TEST di Effetto Halls		
	Op. 40 Verificata lunghezza guaina cavi motor (CPN 39132311): 36 in = 91 cm		
	Op. 80 Verificata direzione olio valvola unidirezionale		
	Op. 130 Verificato che non ci sono torsioni dei tubi:		

NO



		SI	NO
	Op. 190 Scheda PP compilata con: **CPN Bypass Valve, S/N Bypass Valve**		
S1	Op. 200 Scheda PP compilata con: **CPN AC Air Cooler, S/N AC Air Cooler**		
	Op. 360 Scheda PP compilata con: **CPN Motor Fan 1, S/N Motor Fan 1**		
	Op. 380 Misurati 2.5-3 cm tra la ventola e il motorino		
	AL TERMINE: Segnato le viti tirate		

CHECKLIST NOF3

		SI	NO
F2			
	Op. 10 Scheda PP compilata con: **CPN Control Panel, S/N Control Panel**		
	Op. 30 Inserita scheda nel DRIVE del pannello relativa alla potenza motore e modello		
	Op. 30 Scheda PP compilata con: **CPN Starter Box, S/N Starter Box**		
	Op. 90 Collegati i cavi dei trasduttori al XE controller		
	Op. 110 Collegati fili (L1, L2, L3) e messa a terra nel filtro		
	Op. 1180 Scheda PP compilata con: **CPN Separatore 2, S/N Separatore 2**		
	Op. 1220 Scheda PP compilata con: **CPN Valve Moisture, S/N Valve Moisture**		
	Scheda PP compilata con: **CPN, S/N** di TUTTE le safety valves		
S2			
	Op. 60 Controllata apertura verso l'esterno della valvola di non ritorno E il pin montato in posizione verticale E i tappi verso l'alto		
			
	Op. 60 Tubo in posizione 7 collegato sotto (verso il basso)		
	 		
S3			
	Op. 80 Cavi lasciati non troppo corti dopo il collegamento		
	Op. 105 Tutti i connector sono stati collegati		
	Op. 110 Collegati fili (L1, L2, L3) e messa a terra nel filtro		
	Op. 140 Starter coperto con coperchio		