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CoLLaboratE

Co-production CeLL performing Human-Robot Collaborative AssEmbly

D2.1 – End-user requirements, use cases and industrial scenarios (preliminary)

Due date: M9

Abstract:

This deliverable presents the methodological aspects identified and defined, used for deriving the detailed use cases and scenarios, together with a short description of the use cases that will be implemented.

The use cases description has a double purpose, description of functional and operational features of the use cases and description of the desired functional features from which the CoLLaboratE project will extract and details the architectural features to be implemented in the CoLLaboratE system.

Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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EXECUTIVE SUMMARY

The present document is a deliverable of the CoLLaboratE project, funded by the European Commission's Directorate-General for Research and Innovation (DG RTD), under its Horizon 2020 Research and innovation programme (H2020). This deliverable will present the methodology defined and used for deriving the detailed use cases and scenarios as well as the user requirements. The Use cases description has a double purpose, description of functional and operational features of the Use Cases and description of the desired functional features from which the CoLLaboratE project will extract and detail the architectural features to be implemented in the CoLLaboratE system. It is strongly emphasized that this is an ongoing document that is being evolved along with the project progress and will be regularly updated in order to reflect up-to-date information.

This deliverable aims at the identification and description of the use cases ad user requirements of the CoLLaboratE project. The use-cases will be introduced in chapter 3, while chapter 1 and 2 respectively describe an introduction of the current manufacturing landscape and the description of the parameters and approaches to be considered in the identification and description of a Collaborative workcell.

The Deliverable D2.1 will collect the first high level description of the Use cases. A final version of the deliverable associated with Task 2.1 is expected at M24. The latter will be a more detailed and complete review of the Use-Cases; it will be considering and describing eventual modifications due to adaptation occurred as a consequence of the design of the final workcell demonstrators. It is important to underline that the description of the four reference use-cases in chapter 3 is limited to a PUBLIC confidentiality level. More detailed descriptions containing data required in Chapter 2 that are considered confidential by the partners are provided as partnership internal and confidential information.

D2.1 is also related with D2.3 (due at M12). In D2.3 the detailed architecture and system specifications will be provided at a preliminary version; user requirements will be used to extract detailed functionality requirements with the aim to define the required architecture of the CoLLaboratE system. Some of the information defined in Chapter 2 have not been detailed in this deliverable but will be provided in D2.3 within the architectural requirements analysis context.

Deliverable D2.1 includes also a copy of the open online questionnaire that has been promoted by the CoLLaboratE project at the European Robotic Forum 2019 in Bucharest and is related to high level user requirements. The results are preliminary since the questionnaire is still available online and the analysis will be included in the final version (D2.2 at month 24).

This deliverable has been shared with the projects advisory group; their feedbacks is described in paragraph 4.1 and will be integrated in D2.2.

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ABBREVIATIONS AND ACRONYMS

Table 1: Partners short names

Partner's short name	Partner's full name
AUTH	ARISTOTLE UNIVERSITY OF THESSALONIKI
CERTH	CENTRE OF RESEARCH AND TECHNOLOGY HELLAS
ARMINES	ASSOCIATION POUR LA RECHERCHE ET LE DEVELOPMENT DES METHODES ET PROCESSUS INDUSTRIELS
JSI	INSTITUT JOZEF STEFAN
IDIAP	FONDATION DE L'INSTITUT DE RECHERCHE
UNIGE	UNIVERSITA DEGLI STUDI DI GENOVA
KU Leuven	KATHOLIEKE UNIVERSITEIT LEUVEN
LMS	UNIVERSITY OF PATRAS
CRF	CENTRO RICERCHE FIAT SOCIETA CONSORILE PER AZIONI
BOR	BLUE OCEAN ROBOTICS
ASTI	AUTOMATISMOS Y SISTEMAS DE TRANSPORTE INTERNO SA
KOL	KOLEKTOR ORODJARNA NACRTOVANJE IN IZDELAVA ORODIJ TER ORODJARSKE STORITVE D.O.O.S
ARCELIK	ARCELIK A.S.
ROMAERO	ROMAERO S.A.

Table 2: Abbreviation and Acronyms Part 2

Abbreviation	Description
AGV	Automatic Guided Vehicles
AI	Artificial Intelligence
AMR	Autonomous Mobile Robots
AOI	Automated Optical Inspection
CE	European Commission
CEN	European Committee for Standardization
COBOT	Collaborative Robot
DEAV	Daily Exposure Action Value
DELV	Daily Exposure Limit Value
EC	European Commission
EN	European Standard
ESD	Electro Static Discharge
HG	Hand guiding
HMI	Human Machine Interface
HRC	Human Robot Collaboration
HTV	Hand-transmitted vibration
IPR	Intellectual Property Rights
ISO	International Organization for Standardization
JPH	Job Per Hours
KPI	Key Performance Indicators
MES	Manufacturing Execution System
OEE	Overall Equipment Efficiency
PFL	Power and force limiting by inherent design or control
PL	Performance Level
SMS	Safety-rated monitored stop
SPC	Statistical Process Control
SSM	Speed and separation monitoring
TAED	Target Actual Efficiency Downtime
TS	Technical Specification

DEFINITIONS

In the following text few terms are used with a specific meaning; in order not to generate misunderstanding few definitions are given in the following introductory chapter

Collaborative Robot:

According to ISO 8373:2012 [3], Collaborative Robots are robots designed for direct interaction with a human, while the definition in the ISO 10218-2:2011 adds an important detail: "robot designed for direct interaction with a human within a defined collaborative workspace, where the collaborative workspace is the workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation.

End-User:

The industry or party which utilizes the robotic technology into its premises. The end-user is the owner of the robotic workcell; it covers the costs of its installation and is legally responsible for any consequence of the workcells.

Operator:

The human employee performing its manual work in a workcell; in case of Human-Robot-Collaboration the operator is the actor cooperating with the COBOT in the collaborative workcell.

Takt Time:

Takt time is the average time between the start of production of one unit and the start of production of the next unit, when these production starts are set to match the rate of customer demand.

1 INTRODUCTION

Human Robot Collaboration is a rapidly emerging technology which is expected to have an important impact on future manufacturing design approach in many industries ranging from the automotive manufacturing to retail, food, electronics, consumer and so on. Among the reasons that create this expectation there is the possibility to exploit the physical abilities of the robot such as precision, repeatability and force together with the human operator cognitive (intelligence, problem solving, improvisation, immediate vision) and physical (manipulation, dexterity) capabilities.

Secondarily it is possible to:

- reduce the ergonomic issues using the robots to:
  - carry over heavy operations;
  - Execute high frequency repetitive operations;
  - Substitute the operator in awkward positions;
- improve quality by:
  - robot's characteristic repeatability;
  - the introduction of controlled adaptive constraints in the operator's activity;
  - the direct use by the robot of tools for measurement and objectivation (to perform an objective measurement/control that certifies and tracks the result of the measurement or the effective completion of an operation for traceability and later controls);
- improve productivity using the robot to perform "Non Value-Added Activities" (NVAA: percentage KPI describing the sum of duration of the operations times that are not creating value for the product over the total execution time) instead of the operator;
- give support to elderly or reduced work capacity operators and reintroduce them in the workforce, and so on.

Based on the specific use case, the benefits could be more than the reported ones. It is evident anyway that currently Human-Robot Collaboration is a promising technology offering many new possibilities. The current availability of robotic technologies and the completeness of the regulatory framework allow the implementation of HRC application in production but while the ISO standards are required for the proper design of the workplace and the cell, the design and use of a HRC application in production has to be motivated by a proper benefit analysis. In fact, even though currently many use cases are declared and tested, their diffusion of safe and effective applications is not so widespread.

It is important to note that in the HRC workstations and work applications it is required to harmonize the activities of a robot and a human operator. Current approaches and tools are not suitable for the purpose.

This deliverable aims at the identification and description of the use cases of the CoLLaboratE project. The use-cases will be introduced in chapter 3, while chapter 1 and 2 respectively describe an introduction of the current manufacturing landscape and the description of the parameters and approaches to be considered in the identification and description of a Collaborative workcell.

1.1 INDUSTRIAL USE-CASES OPTIMIZATION CRITERIA

CoLLaboratE project is studying the common and differentiated production criteria implemented by each use case, in order to identify the specific needs for integrating collaborative robotics systems within the different stages of production. Ultimate goals of the end users are – assuring the desired productivity stated by the current market needs and the quality of the product as well as the well-being of the workers.

Criteria and Key Performance Indicators (KPIs) that are used to evaluate the current production are mostly linked to performance, quality and safety. More precisely the time frame (Takt time) constitutes an important metric, showing how much time is required to produce a piece, and consequently how many pieces are produced per a unit of time.

Concerning quality, it is evaluated by visual inspection in most of cases by following ISOs, precise protocols and internal rules. The quality control is not focused only on products but also covers the production processes (supply, problem detection etc.).

Finally, the workers' safety and ergonomics are also evaluated based on standardized methodologies. In CoLLaboratE project, ergonomic assessment scores will constitute an important KPI to investigate how the project will contribute to the detection of ergonomic issues, but also how HRC will improve workers' safety.

1.1.1 Industrial Organization

Industrial organization is mainly reflected on serial production and assembly lines system. It means that the final product is obtained through a scientific serial organization of the work: the production system is divided in elementary standardized operations with a specific execution time. Each operation is then strictly dependent on the previous one and on the next one. The industrial organization considered in the CoLLaboratE project refers to: durable goods industry (ARCELIK), automotive Industry (described by CRF, that is the main Research Centre of FCA in the EMEA region and is expert in the FCA manufacturing process), aerospace industry (ROMAERO), and component maker (Kolektor) who develops, produce, and distributes customer-specific components and solution.

Taking the use-case of ARCELIK, who has operations in a durable consumer goods industry with production, marketing and after-sales services, all manufacturing processes are designed for serial production of white goods. The average cycle time for the processes is around 25-30 seconds, with 18 seconds cycle for the assembly lines. TV production is an example of serial production, (1300 products are produced by a single line in a single shift), and it is the most difficult one compared to other white goods, due to the high number of cabling and socketing operations. As a result, automation level is much lower with respect to other white goods.

Respectively, the automotive industry, described by CRF, follows the assembly line production system. The production of the automobile starts with the development of the car body through the joining of the printed metal sheets. Once the skeleton is ready, after the cataphoresis process, it is painted and finally, the engine, the electrical cables and internal parts are assembled. In order to improve the efficiency of the whole process, the suppliers of components (engine, wheels, trims) are located in strategic positions with respect to the specific Plant.

Likewise, the manufacturing business of ROMAERO comprises a series of industrial activities like: Processing of sheet metal; Machining; Special processes; Composite materials; Tool design; Assembly (riveting assemblies, cold working of holes, torque loading, aircraft bond and ground bonding assemblies, welding, brazing). A considerable proportion of the commercial programs running in ROMAERO involve serial manufacturing of parts and components for aircraft and/or equipment OEMs and their suppliers. Nevertheless, these programs have not been judged appropriate for the implementation of collaborative robots, in the context of the CoLLaboratE project.

Serial production is also adopted by Kolektor that provides customers with the whole solution, from samples to large scale industrialization with state-of-the-art technologies. The type of production is usually adapted to the product and quantities but is mostly serial with full automation of manufacturing and assembly processes, with robot integration where applicable. Each production line is designed for minimal human intervention, with part feeding mechanisms and buffers.

1.1.2 Productivity

For the majority of CoLLaboratE's Use Cases, production lines structure is the proper one for the standardized goods produced in large quantities with a constant flow of materials and with a predetermined time frame (tack time).

At Arcelik, for the TV electronic card assembly operation, cycle time (the time needed to complete the operation) is the major performance metric (KPI). Any delays in the operation time will be directly affecting the entire production line due to continuous production. Current cycle time for the entire operation is 21 seconds. Other KPI's are Electro Static Discharge (ESD) scrap rate, due to screwing and miss-screwing. Improving the cycle time together with the new HRC production cell is targeted.

In automotive field, based on the type of product (premium brand or mass-market brand) and number of vehicle produced, the plants have different tack time. As described by CRF, the production process is divided in four main areas (or Operating Units): The Press Shop, The Body in White (BIW), the Paint Shop, and the Final Assembly. BIW, Presses and Painting shops have a high rate of automation; BIW is the shop floor with the highest concentration of robots: it is equipped with robots and numerous fully-automated welding and adhesive application stations operated by highly-skilled personnel. The Paint Shop, like BIW, is also an area that is highly automated.

The final area of the production process, the Final Assembly, guarantees high flexibility in product mix and customization models; that's why in this area the presence of humans is fundamental.

In Assembly all processes are manual and the Takt time is determined according to the production needs; it can eventually be limited if technological bottlenecks are present. The MTM (Methods-Time Measurement) analysis is used to organize, on the basis of the tack time, the activities and saturation of each single operator (cycle time). New developments have led to the MTM-UAS (Universal Analyzing System) aiming at the continuous improvement of:

- cost-performance ratio (function, quality)
- delivery reliability (short-term, on time deliveries)
- human and motivating work design

The MTM-UAS goes toward considerations related to new, more flexible, models of work.

In order to guarantee the productivity goals of each product, each Operating Unit (Press Shop, Body In White, Paint Shop and Final Assembly) is divided in Elementary Technological Units, autonomous and independent production cell controlled by the unit leader. The rigidly vertical structure of the traditional plant is replaced by decentralization. Overall, the production models usually follow the structure of the lean production.

Always according to the production needs (determined by the JPH – Job Per Hours – which defines the number of vehicle produced per hour) the production can be organized in shifts (from 1 to 3 of the duration of 8 hours). Eventually each shop floor can organize the number of shifts differently.

Concerning the production of the sliding ring hybrid component by Kolektor, it has a 24/7 production run and a timing of 29 s/part. The capacity of the production line is 800.000 parts per year at 80% OEE (20% scheduled loss for predictable down times). OEE is the ratio of *Fully Productive Time* to *Planned Production Time*. Actual OEE is evaluated based on three loss factors:

- Availability loss
- Performance loss
- Quality Loss

Schedule Loss is not included in OEE calculations since there is no intention of running production. KPI metric used in Kolektor production facilities is TAED standing for Target, Actual, Efficiency, Downtime:

- Target (a real-time production target driven by the planned rate of production)
- Actual (the actual production count)
- Efficiency (the ratio of Target to Actual; how far ahead or behind production is running)
- Downtime (accumulated unplanned stop time for the shift)

In case of ROMAERO, and the assembly of the float, the productivity, a measure of the efficiency of production, is not a relevant parameter, given the small number of assemblies per order.

1.1.3 Quality

Quality is a factor of great importance not only when it pertains to product value but also to product compliance to safety standards. Depending on product system, internal control strategies are integrated within the production phases. The quality control of products and processes is carried out at all stages of development and production, from the technological concept to the industrialization phase. Visual quality controls are performed most of the times within the different operations, so human presence is essential.

In automotive industry, as described by CRF, quality control is part of the product development process. In fact, quality can be ensured through the identification and the elimination of the root causes and not only through final controls and deliberates. In the Final Assembly Operating Unit, in particular, where the level of automation is low, the workers are responsible in guaranteeing the quality in each operation. Poke Yoke (simple devices/solutions that prevent mistakes in the human operations) solutions are used when possible. Whenever quality impacts on product safety, objectivation of performed operations is done. In some cases the assembly operations are defined specifically to obtain the desired quality. Dedicated personnel make the quality controls and, at the end of the line, all completed vehicles are then subjected to a "Dynamic Performance Test" over a mixed driving route. For quality control, the Quality Unit plays a vital role in ensuring that production conforms to the most stringent "ISO 9001" quality management standards. The Process, Product, Supply and Diagnosis areas of the Quality unit are responsible for monitoring and managing aesthetic, performance and statistical checks and controls for each vehicle. Quality Unit inspects components from external suppliers, analyses conformity of all BIWs and vehicle systems, conduct periodic performance audits and issue guidelines for improvements in production processes.

TV production is similar to semiconductors with respect to the clean room and Electro Static Discharge (ESD) requirements. Electronic cards that will be handled and screwed during the collaborative assembly should satisfy all the TV quality standards. The entire list of Arçelik's quality certifications and standards can be seen at this link [21]. Scrap rates due to miss-screwing and ESD violation are measured at the performance test stations located at each end of line. Reasons for both scraps are related to operator negligence. HRC is expected to contribute to the elimination of these issues in the production cell. Visual inspection will be used to count the number of screws and operation completion.

When it comes to the design, manufacturing and assembly in the aerospace industry, quality is of prime importance as it is directly connected to the safety in exploitation. The manufacturing and assembly of the float makes no exception. The means by which an adequate level of quality is ensured for the final product are multiple:

Selection (recruitment) of highly skilled workers, b) Continuous training of the workers, c) Assembly using standardized materials and tools, d) Implementation of standardized processes, e) Final control and verification of the process output, against standardized values, f) Step-by-step, continuous control and verification of the process output, against standardized values.

The assembly process of the float contains a variety of sub-processes out of which the riveting sub-process is the only one of interest for CoLLaboratE. Should one human worker be replaced with a collaborative robot for the riveting sub-process (the worker holding the bucking bar), points a) to d) above will remain unchanged. Point e) however, will be affected, as the quality control for each rivet is currently ensured by the human operator, through direct observation and based on experience. The quality control will still need to be performed by the human operator, but the robot will need to be fitted with an adequate interface to provide the required data to the human operator so that he/she can assess the quality of the performed work. In addition, the human operator will need to communicate with the robot to instruct it on how to proceed next: continue with the riveting on the same rivet (if he/she concludes that the quality of the riveting is not satisfactory) or move to the next rivet. In the latter case, the robot will need to understand what the next rivet is.

For the control of the riveting process using conventional rivets, the following two internal specifications (owned by Bombardier) are used: 1- (Bombardier Aerospace Process Specification) BAPS 151-01, Revision B, 9/06/2010 – *Installation of conventional rivets*. 2-(Bombardier Aerospace Process Specification) BAPS 157-028, Revision G, 12/10/2016 – *Pressure and environmental sealing*.[1]

Based on the two specifications, the quality of the riveting is assessed visually, at the end of each riveting session. For each type of rivet, the upset (shop) head is measured (the dimensions are actually estimated by the workers). Both the diameter and the height of the upset head must have values between a MIN and a MAX value, as specified in BAPS 151-01. Other geometrical features are specified in the standard, along with the acceptable values for compliance.

Similarly, at Kolektor, the production process uses several procedures and technologies to evaluate the quality of the produced parts with the main ones being SPC (Statistical Process Control) of all components and the finished product and an electrical test of the connection terminals. The 100% in line optical inspection is also a part of some of the production lines. The goal of the quality assurance is to optimize and lower the current PPM rejection rate.

ISO 9001 standard dictates that a way of preventing mistakes and defects in manufactured products and avoiding problems when delivering products or services to customers must be implemented as part of quality management. It is focused on providing confidence that quality requirements will be fulfilled.

Statistical process control (SPC) is a method of quality control which employs statistical methods to monitor and control a process. This helps to ensure that the process operates efficiently, producing more specification-conforming products with less waste (rework or scrap). SPC can be applied to any process where the "conforming product" (product meeting specifications) output

[1] the two BAPS are not public documents. The information contained within is only accessible to ROMAERO's personnel.

can be measured. Key tools used in SPC include run charts, control charts, a focus on continuous improvement, and the design of experiments.

1.1.4 Safety and Ergonomics

Each use-case is in compliance with different ISOs and national or international guidelines, regarding the ergonomic risks, found mostly in less automated processes.

In automotive field, the Final Assembly is the less automated part of the process. That's why, here in particular, the attention to ergonomics of the workers is a fundamental aspect. The main critical aspects from the ergonomics point of view refer to the load handling and to the repetitive operations. So, whenever possible, precautions are taken to make the workstation as ergonomic as possible, for instance manipulators are used for lifting loads or the effective management of work organization is used to facilitate repetitive operations. However, innovative solutions are required.

The ergonomic risk assessment of the workstations is based on the ergonomic indexes normally used by the company and the ergonomic analysis methods available. Many commercial software integrate the analysis tools and support the design, like, for instance, the "Jack" software (part of PLM Siemens). The reference risk indicators used are the corporate risk index (EAWS) and the regulatory risk index (in particular for standards 11226, 11228 and 1005).

Each work operation is investigated evaluating postures through ISO 11226 and EN 1005-4, forces through EN 1005-3, manual handling through EN 1005-2, ISO 11228-1, ISO 11228-2 (loads more than 3 kg) and EN 1005-5, ISO 11228-3 (loads less than 3 kg and high frequency). In Jack many international methods for ergo analysis like RULA, OWAS and NIOSH LI are available. The EAWS index [11], is a holistic system (full coverage of all risk areas) and it provides detailed results in four sections: body postures, action forces, manual materials handling, and upper limbs.

Table 3: Risk areas, correlated standards and most common ergonomic tools

	Standards		Tools		
Risk Areas	**CEN**	**ISO**	**2nd Level**	**1st Level**	
Body Postures with low external effort	1005-4	11226	OWAS	AAWS	EAWS
Action Forces	1005-3	11228-2	SNOOK-CIRIELLO TABLES		
Manual Material Handling (Repositioning)	1005-2	11228-1	NIOSH		
Upper limbs – high frequencies / low loads	1005-5	11228-3	OCRA STAIN INDEX HAL-TV		

The generic methods of ergonomic assessment like RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) are also frequently used to calculate the ergonomic risks of the operations. REBA score before and after the HRC production cell will constitute an important KPI for the CoLLaboratE project.

ROMAERO is particularly concerned by ergonomic issues, and beyond following national guidelines [2] it has established a Plan for Prevention and Protection. It is updated on a regular basis along with the changes in the company's activity, the new types of processes and the changes in legislation. The development of a technology for collaborative riveting capable of replacing one technician that is usually exposed to high level of vibrations is a considerable progress in the field of work-related ergonomics in ROMAERO.

In December 2018 an analysis of the level of exposure to vibration for different categories of technicians was performed in ROMAERO, including the technicians performing the riveting for the assembly of the float. The analysis was performed in accordance with the standard SR EN ISO 5349 - Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration.

The analysis performed in 2018 (concluded with the internal report 1217/12.12.2018) produced a series of recommendations towards the improvement of the conditions at the workplace, in ROMAERO, among which:

- Provision of the concerned technicians with dedicated equipment for protection against vibration;

[2]

- Internal documentation targeting the reduction and removal of health and safety risks at the workplace.
- **Law 319/2006 updated in 2012 and in 2018**, concerning the safety and health at work;
- **Romanian Government's Decision 1425/2006** for the approval of the implementation methodology for law 319/2006 (see above);
- **Romanian Government's Decision 1876 from December 22nd, 2005**, concerning the minimum requirements for safety and health with respect to the workers' exposure to risks generated by vibrations;
- **Romanian Government's Decision 355/2007 updated in 2012 and 2013**, concerning the monitoring of workers' health.

- Allowing the concerned technicians to take a sufficient number of breaks during the working hours.

Concerned by the wellbeing and safety of its employees, Kolektor was awarded the OHSAS 18001 certificate which is a standard that provides the organizations with the elements of an effective safety management system which can be integrated with other management systems and help organizations achieve better occupational health and safety performance. Every aspect of the production processes is designed in accordance with these standards.

1.2 Human Robot Collaboration rules according to ISO Standards

HRC is a new work approach whose implementation and use is allowed by a newly available technology (Collaborative Robots: COBOTS) and new ISO Standards for the safety in industrial environment. HRC in manufacturing impacts on aspects related to Human performance (ergonomics), productivity and inherent quality and it is more and more used worldwide.

The ISO regulatory framework for Human Robot Collaboration nowadays is properly defined and any application at industrial level needs to consider it. It is important to underline that the use and application of standards is voluntary in most countries. Technical standards only become mandatory if they are referred to in contracts, laws or regulations. In addition, contract partners may choose to make the use of a standard binding. Standards are often used to settle legal disputes, especially in product liability cases. Courts use standards to help decide whether or not the manufacturer has followed the acknowledged rules of technology and thus has exercised "due diligence". Standards are thus recommendations which, when followed, provide legal certainty. Standards become thus a technical reference that end-users have to consider as a best practice. It is not compulsory to follow the technical standards, but in case of accidents involving Human Operators, the end-user has to demonstrate that he applied any reasonable know-how and existing solution to guarantee operator's safety. If the end-user decides not to use existing ISO-Standards, he has to explain and demonstrate that the solutions he took are sufficient to guarantee full operator's safety and laws conformity. On the contrary, although the use of standards which are referred to in legislation does not absolve one of liability, the "presumption of conformity" principle applies. This means that when a manufacturer or end-user complies with legal provisions laid down in a directive or law by applying the relevant standards, it can be presumed that the product (the workcell in case of Human-Robot Collaboration) is in conformance with these provisions and can thus be placed on the market.

The CE Marking (defined and regulated in the "Machine Directive 2006/42/EC" which a mandatory European regulation) demonstrates conformity with the essential safety requirements laid down in EU legislation. The CE mark has to be applied by the manufacturer or exporter, or their representative. Some directives require conformity assessment by a neutral third party, called a "notified body", before the marking can be applied. By applying the CE mark a manufacturer declares on his/her sole responsibility that the product meets all the legal requirements and can thus be placed on the EEA market.

The CE mark on Robots should not be applied since robots are considered partly completed machinery. Partly completed machinery are almost machinery but cannot in itself perform a specific application. They are only intended to be incorporated into or assembled with other machinery or other partly completed machinery (or equipment, thereby forming machinery or assemblies of machinery) and must thus undergo further construction in order to become final machinery that can perform its specific application.

Partly completed machinery alone cannot comply fully with the essential health and safety requirements since certain of the risks may result from the fact that the machinery is not complete or from the interface between the partly completed machinery and the rest of the machinery or assembly of machinery into which it has to be incorporated (this is the case of the collaborative “safe” robot with a gripper, handling a dangerous part: the whole system cannot be safe and thus certified). However, the manufacturer of partly completed machinery must state, in a *Declaration of Incorporation*, which of the essential health and safety requirements he has fulfilled.

Similarly, assemblies of machinery (with or without partly completed machinery) are subject to the Machinery Directive as machinery themselves because their safety depends not only on the safe design and construction of their constituent units but also on the suitability of the units and the interfaces between them.

If the new unit (machinery or assembly of machinery) is constituted by partly completed machinery accompanied by a Declaration of Incorporation and assembly instructions, the person incorporating the partly completed machinery into the assembly is to be considered as the manufacturer of the new unit. He must therefore:

- assess any risks arising from the interface between the partly completed machinery, other equipment and the assembly of machinery;
- fulfil any relevant EHSRs that have not been applied by the manufacturer of partly completed machinery;
- apply the assembly instructions, draw up an EC Declaration of conformity and affix the CE marking to the new unit as assembled.

In case of assembly of machinery the CE-marking will thus be applied only to the whole assembly [1] [2].

The Main HRC regulatory technical framework is mainly based on the following standards:

- EN ISO 10218-2:2011 [5] that sets the allowed behavior of the COBOT in Human Robot Collaboration applications, through the definition of the collaborative modes and the rules for the integration in the collaborative workspace (targeted to integrators);
- EN ISO 10218-1:2011 [4] that sets the hardware and functional safety characteristics that a collaborative robot has to fulfil (targeted to robot’s constructors);
- ISO/TS 15066:2016 [6] sets the numerical limits for the physical KPIs (velocity, force, power…), and the methodologies for the workplace safety in Human Robot Collaboration (HRC) applications.

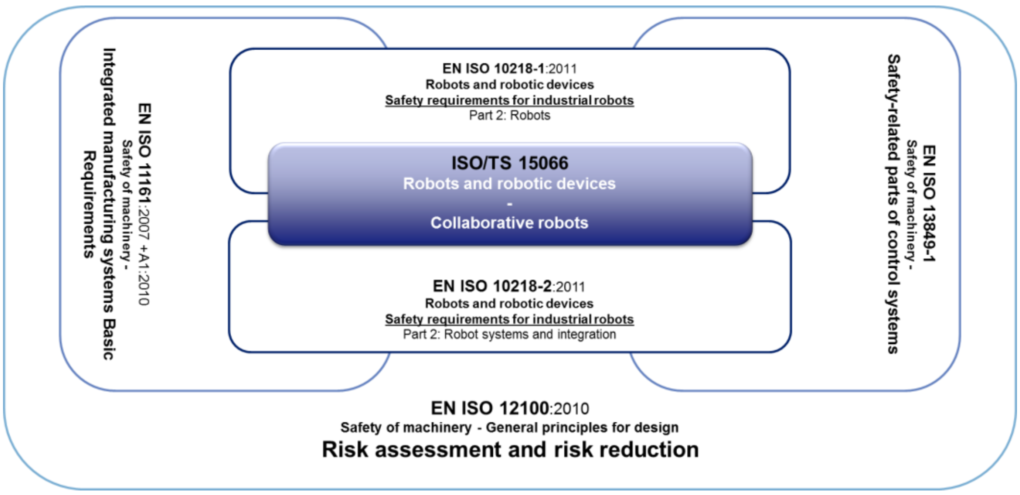


Figure 1: Main ISO Standards related to Human Robot Collaboration

For those parts of the whole workcell that don't have a specific technical standard for regulation (e.g. AGVs, AMRs or Grippers for manipulating COBOTs), the references is the Machine Directive (in Europe), or any other technical standard related to the specific device depending on functional and safety similarities.

The main reference standard is the ISO 10218-2:2011 that defines the rules for the System integration of collaborative robots. According to ISO 10218-1 [4], *collaboration is a special kind of operation between a person and a robot sharing a common workspace. It is only:*

- *used for predetermined tasks;*
- *possible when all required protective measures are active;*
- *possible for robots with features specifically designed for collaborative operation complying with ISO 10218-1 [4].*

Furthermore, *due to the potential reduction of the spatial separation of human and robot in the collaborative workspace, physical contact between the human and the robot can occur during the operation. Protective measures shall be provided to ensure the operator's safety at all times.*

The collaborative workspace is the space where the Operator(s) *can interact directly with the robot, and shall be clearly defined (e.g. floor marking, signs, etc.). Persons/operators shall be safeguarded by a combination of protective devices and compliance with robot performance features allowed in ISO 10218-1 [4]. The design of the collaborative workspace shall be such that the operator can easily perform all tasks and the location of equipment and machinery shall not introduce additional hazards.*

A complete risk assessment is required for any application involving collaborative operation specifying collaborative methods, physical parameters (power, force…), ergonomics, additional tools and so on. The whole robot system and application shall be included in the risk assessment and certified for safety.

ISO 10218-2:2011 gives the fundamental definition of the collaborative operations in the collaborative workspace.

When designing a collaborative operation, the standard defines four possible collaborative modes, each characterized by its own specific functionality and safety requirements.

Any detected failure of the selected safety features of the collaborative operation shall result in a protective stop. After the stop, autonomous operation shall not be resumed until the reset by a deliberate restart action outside the collaborative workspace. The allowed Collaborative modes are the following:

- **Safety-rated Monitored Stop (SMS):** If there is no person in the collaborative workspace the robot operates autonomously. If a person enters the collaborative workspace the robot shall stop moving and maintain a safety-rated monitored stop in order to eventually allow direct interaction of an operator and the robot (e.g. loading a part to the end-effector); the robot's operations can resume after the person leaves the collaborative workspace.

- **Hand Guiding (HG):** Hand guiding operations are a manual guidance of the end-effector of the robot performed by the operator. For HG:
  - the task is carried out by manually actuating guiding devices located at or near the robot end-effector;
  - the operator uses a hand-operated device to transmit motion commands to the robot system;
  - when the robot reaches the hand-over position, a safety-rated monitored stop, must be set;
  - the operator shall have clear visibility of the entire collaborative workspace;

  - robot systems used for hand guiding can be equipped with additional features, such as force amplification, virtual safety zones or tracking technologies;

- **Speed and Separation Monitoring (SSM):** The Robot system is designed to maintain a safe separation between the operator and the robot in a dynamic manner (considering position and speed of both the Human operator and the Robot). Robot speed, minimum separation distance and other parameters shall be determined by risk assessment. In SSM mode:
  - The robot system and operator may move concurrently in the collaborative workspace.
  - During robot motion, the robot system never gets closer to the operator than the protective separation distance (or the robot system stops).
  - Speed and separation monitoring shall apply to all persons within the collaborative workspace.
  - For constant values of speed and separation, the maximum permissible speed and the protective separation distance shall be determined through the risk assessment as worst cases over the entire course of the application.

- **Power and Force Limiting by design or control (PFL):** The Robot systems are designed to control hazards by power or force limiting to specific values depending of the type of possible contact and risks related to them. Parameters of power, force, and ergonomics shall be determined by risk assessment. Some important requirements in PFL are:
  - PFL collaborative operation requires robot systems specifically designed for this particular type of operation.
  - Physical contact between the robot system (including the workpiece) and an operator can occur either intentionally or unintentionally;
  - Risk reduction is achieved, either through inherently safe means in the robot or through a safety-related control system
  - Risk reduction shall consider means by which possible contact between the operator and robot system would not result in harm to the operator (soft layers around the robot);
  - Objects with sharp, pointed, shearing or cutting edges, such as needles, shears, or knives, and parts which could cause injury shall not be present in the contact area.
  - Contact exposure to sensitive body regions, including the skull, forehead, larynx, eyes, ears or face shall be prevented whenever reasonably practicable.
  - In any clamping event between the collaborative robot system and human body the person shall be able to escape independently and easily from the clamping condition.
  - If robot motion can result in clamping or pinning a body area between a part of the robot and another item in the robot cell, the robot speed shall be limited
  - For frequent contacts or other special cases, the applicable threshold limit values can be further reduced to an ergonomically acceptable level.
  - Parameters of power, force, and ergonomics shall be determined by risk assessment.

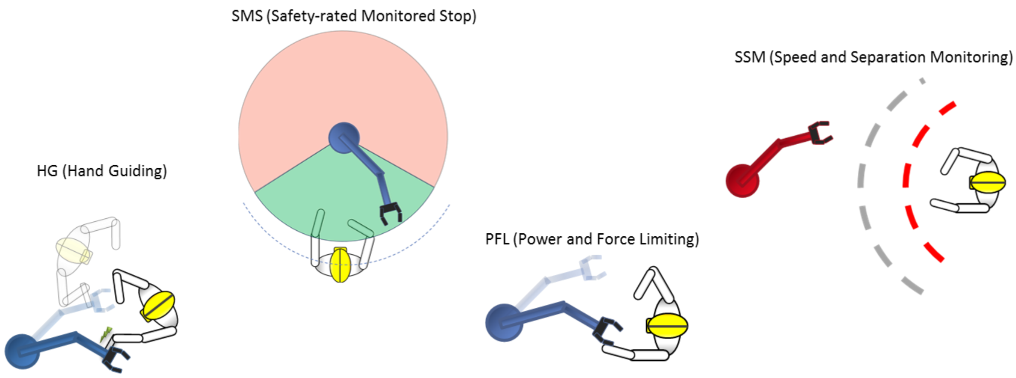


Figure 2: Collaborative Operating Methods

Any HRC application has to be defined by one or more collaborative modes and the change point between autonomous and collaborative operations shall be designed so that the robot cannot endanger personnel. Any robot or safety device used in a collaborative workcell shall comply with ISO 10218-1.

The ISO 10218-1 [4] defines the Hardware safety requisites of the robot and devices in the collaborative workspace, their Performance Level (PL) and Structure Category (control redundancy requisites). For collaborative robots, and in general for safety related devices in a Collaborative Workspace a PL "d" with Safety category 3 is required (Figure 3).

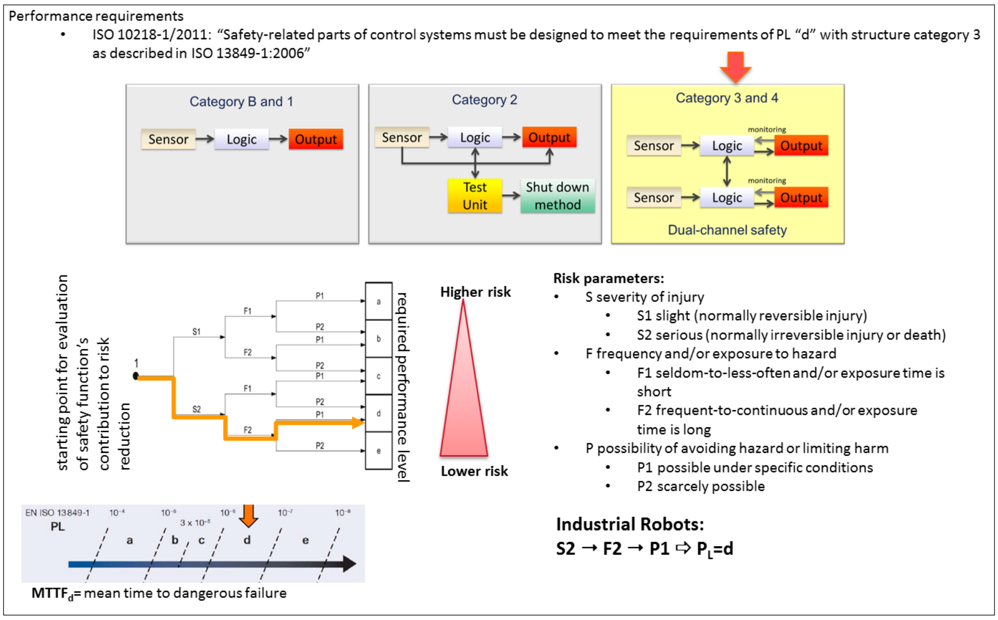


Figure 3: Safety requirements for Collaborative Robots

ISO 10218-1 [4] defines also all the functional behavior and characteristics of any protective devices to be used in the four collaborative modes.

In 2016 the ISO/TS 15066 [6] was released. This technical specification defines the details for the safety in HRC work-places and work-applications, and gives numerical values for the calculation of Speed, Force and Power limits to be used in the design of HRC work-cells.

The general rules for the realization of a collaborative workcell can be thus summarized as:

- *The requirements for the design of the collaborative robot operation are provided in ISO 10218-2:2011, 5.11.*
- *The operating methods (SMS, SSM, HG, PFL described after) may be used singularly or in combination when designing a collaborative application.*
- *Transitions between methods of collaborative operation or between non-collaborative operation and collaborative operation shall be designed such that the robot system shall not pose unacceptable risks to the operator*
- *If a collaborative robot system relying upon safety-rated limiting functions is used without an enabling device, then these functions shall always remain active.*
- *Any detected failure in the safety-related parts of the control system shall result in a protective stop and in this case operation shall not resume until reset with the operator outside of the collaborative workspace.*
- *All people within the collaborative workspace shall be protected by protective measures.*
- *During collaborative operation the operator shall be able to:*

  - *stop robot motion at any time by a single action OR have an unobstructed means of exiting the collaborative workspace*
  - *transitions between collaborative operation or between non-collaborative operation and collaborative operation shall not pose risks to the operator*
- *A visual indicator to identify transitions between collaborative and non-collaborative operations can be used.*

It is important to understand that the risk assessment requires the application to be precisely specified with all its constraints and components. The result is the assessment of risks in the overall application. If the risk is too great, measures have to be used to minimize the risk of the application to an acceptable residual risk (e.g. safely reduced velocity in combination with collision detection. In accordance with EN ISO 10218-1:2011 [4]). The CE mark may only be affixed if the modified risk assessment confirms a sufficiently low residual risk.

The CoLLaboratE Project is defining an architectural solution to the safety of HRC applications which includes the control of all the devices in the loop. One of the additional features that the project will define is the capability to identify behaviors which can generate risks for the operator. In order to achieve this target a basic know how on the reference safety technical standard, as well as a know-how on ergonomics of the operator is defined in the system in order to allow a dynamic correction of the human's behavior.

1.3 Criteria for use cases identification

Current industry (besides of HRC applications) is designed for a traditional approach which implies a physical separation between the machines and the operators. This forma mentis is kept and used even in many collaborative applications, where a kind of separation among the operator and the robot is maintained and it is leading to a widespread use of applications with distance separation (pure SMS approach).

The co-presence of operators and robots (space sharing and collaboration between human and robot that, up to now, was not allowed in industrial applications) deeply modifies the approach to the workspace and application design.

The identification and choice of workplaces and applications that can take proper advantage of the HRC technology is not trivial and requires the comparison with the currently used technology (based on the traditional approach) where the operator and the robot cannot share the same space and cannot co-operate on the same application.

These comparisons are usually made on the basis of measurable parameters normally indicated as KPI (Key Performance Parameter). KPI's are selected measures that provide visibility into the performance of an activity and allow decision-making to achieve the desired results. They help to understand what is working and what needs improvements. Logically, they must be measurable. Considering the measurable nature of an indicator, we can also say that a relevant KPI follows the logic SMART: Specific, Measurable, Achievable, Relevant, Time based. Indicators should be chosen as KPIs only when their achievement would be able to align the process performances with its vision and strategic objectives.

It is important to underline that every industrial manufacturer decides whether to implement HRC according to a cost/benefit analysis to fit the initiative into its innovation plans and costs. This fact implies that:

- The evaluation is based on that specific industry's main KPIs (e.g. Automotive ≠ Health ≠ Avionics ≠ Industrial craftsmanship ≠ Naval…)

- The result of the evaluation can be different according to the existing grade of development in some industries (for example in the automotive sector the ergonomics factors are already deeply considered, thus it is rare that some workcell is not optimized in terms of ergonomics)
- Similar operations can be performed manually in a fixed workstation for a long time, or in a continuous moving in a semi-autonomous operation in a short time.
- Extension and scope of the operations, as well as ergonomic characteristics and requirements, can be extremely different (e.g. Consumer electronics vs Naval Industry)
- The same operation can be performed in line (in a high or low JPH -Job Per Hours-configuration, thus resulting in very low TAKT Time, e.g. 30 s, or high TAKT Time, e.g. >10 min in line) or with mixed manual/autonomous operations in a fixed workspace (single assembly workstation, e.g. niche high target automobiles) or in fixed large workstations (e.g. Train construction, Naval…)

Because of the previous considerations a unique approach to the identification of proper use-cases is not applicable. Nevertheless HRC has a clear impact on some of the most important and common high level KPIs in industry. Independently from the type of industry, HRC impacts all the KPIs that are usually affected by Human Operators; thus HRC impacts on ergonomics/safety, productivity, inherent quality. Collaborative robots can be and are often used as "cheap, flexible robots" even in non-collaborative applications thanks to their programming simplicity; these kind of applications are not considered as reference in the current deliverable which is mainly concentrated to the description of the collaborative phases.

The reference KPIs are many; in this document we concentrate on manufacturing KPIs. The main KPIs that are related to manufacturing and production of goods (and can thus be influenced by the application of COBOTs) can be grouped into three large groups:

- Productivity

  All KPIs describing parameters, behavior, performances that affect the total number of products produced and check if the effective productivity is in-line with the expected one. We even group here KPIs describing economic wastes and losses, production timing respect and so on.
- Quality

  Quality's KPIs are for example those related to the amount of scraps, the number of returned parts, and the defectiveness of the final products due to Man, Machines or Manufacturing processes (Materials affect the quality as well but it is not related to the human/robotic processes).
- Environment, Health and Safety (EHS)

  In relation to the manufacturing processes other important KPIs are Factory's energy consumption (not affected strongly by the use of robotics rather than human operators), Safety and finally Health; Many factors impact on operators' health and can cause both direct (quality defects due to tiredness, stress, disattenction), indirect (absence of operators from the production due to accidents, illness or Muscolo Skeletal Disorders(MSD) and cumulative issues (social costs related to serious illnesses or MSD). To prevent many health problems, in particular MSD, the ergonomics approach is fundamental.

Each of the three groups can be split into more detailed KPIs that:

- are always dependent on the specific process
- describe in a quantifiable way the process in detail
- support the analysis of the production trend

KPIs are strongly process related, thus, it is practically impossible to list all the important KPIs upon which the application of an HRC solution should be defined.

The comprehension of the criteria upon which the HRC applications can be defined requires both the knowledge of the industrial methodologies in the specific process upon which current workplaces are based, and HRC technology both in terms of technical possibilities and State of the Art, and regulatory framework. Finally there is the need to consider the operator's involvement in conjunction with the automation planning. The operator involvement means a proper design of methods, operations and interactions with the robot as well as considerations on reachability, work repetitions, forces, body postures (ergonomics) and so on.

Only few studies have been facing the issues of the identification of proper workcells for HRC, and their approach:

- Zanella et Al. [7] proposed a methodological approach to define the best candidate upon a large set of workcells (e.g. all the cells in a full automotive line);
- Teiwes, et Al. [8] propose an adjustment of the MTM analysis in which an added overall score is calculated through the assignment of a specific score to each kind of operation defined in the MTM analysis. This work gives an interesting approach to a modified MTM, but doesn't cope with the definition of a proper set of KPIs.
- Grahn, et Al. [9] suggest a set of KPIs for the evaluation of potential benefits provided by a cooperative assembly workplace.

It is important to highlight that the set of reference KPIs can vary significantly among use cases.

This is due to the difference in the methods used in production, and in criteria used to select the workcell (that can't be unique, but depend on the target and scope of the analysis). For instance the identification of the best HRC cell in a new Assembly shop in order to reduce costs related to ergonomics is different from the identification of the best HRC cell in an existing paint shop with the aim to improve quality. For these reasons a fixed set of KPIs could be counterproductive.

The set of Parameters is also different when considering the "Brown Field" workcells (i.e. adaptation and renovation of existing workcells) or "Green Field" workcells (i.e. design of HRC workcells starting from the application without strong layout constraints)

- KPs are identified and evaluated according to how the benefit will be evaluated/validated;
- Requested data have to answer to the following questions:
  a) Which cell/application (identification data);
  b) How can the application be described;
  c) PROs: which characteristics of the application or workspace can be improved by the use of HRC;
  d) CONs: which characteristics of the application or workspace can affect negatively the application of HRC;
  e) Benefits: which quantifiable benefit the HRC application can give.

The most significant group of data that need to be taken into account in order to identify most suitable workcells (in brown field case) for HRC are:

- ergonomics and related tools: description of the current ergonomics and tools which are used in production to improve it. These data are used in order to better rank the applications in which ergonomics for the operators is currently critical, or achieved by expensive tools and supports. HRC can improve in these cases the current situation;
- operator's position and room availability: description of the position of the operator, for example, in respect to the vehicle and room availability (for hands and for body) during the operations in order to consider difficulties and risks arising from the co-working in restricted

areas; space in the cell/area in order to evaluate if the robot can be placed without hindering operative and safety areas for the operators;
- conveyor description: description of the conveyor type and its use (stop station, continuous moving...). These factors can affect both the technical complexity and the difficulties for the operator in relation to the application;
- operating time: Takt time, duration of the reference operation, NVAA (Non Value Added Activities) percentage. These data are originated from the MTM-UAS (Methods-Time Measurement - Universal Analysis System) analysis of the cells;
- type of logistics: information about logistics for the specific cell in order to consider impact on the new cell's layout coming from the presence of the robot.

All above parameters are suitable for "green field" as well, but parameters like, for example, logistics, in the brown field case are a constraint, while in the green field logistics has to be designed according to the workcell and it is thus a weaker constraint.

For further design of the workcells it is necessary to define:

- A draft hypothesis of the main phases made for each potential application. The description level gets recursively more and more detailed;
- A concept design of the cells defined in terms of required functionalities and thus in terms of systems and hardware.

The following main aspects should be considered:

- Technological complexity
- HRC need and use
- Benefits/Costs indicator
- Ergonomics & Safety
- Logistic Interface

1.4 KPIs for COBOTs

In the HRC application the COBOT plays a vital role; in an interesting handbook, integrating many different studies on the field, ROBOTIQ (a Canadian company producing flexible grippers for robotic applications) together with UNIVERSAL ROBOTS [12] proposes 5 main KPIs to monitor the performances of Collaborative Robots.

The study starts from considerations on the main characteristics of COBOTs' KPIs that are:

- Non-financial—While it's certainly important to calculate the Return on Investment (ROI) of the collaborative robot, this metric won't tell how to improve its operation.
- Measured continuously—COBOTs make it easy to gather data, since they're able to log it directly within their programs. KPIs should be logged continuously in order to compare both long-term and short-term data and quantify the effect of small changes on the robot's performance.
- Linked with other Operational KPIs—The robot operation affect other KPIs within the business (e.g. time from order to shipment, manufacturing cost per unit, plant downtime). The metrics used for the COBOT should have clear links to broader effects on the business.
- Focused on one or more of the common losses—Many of the performance gains in collaborative robotics can be achieved by tackling some common losses. KPIs that reflect these losses will likely point to ways of improving performance.

- Easy to measure—KPIs that are hard to measure won't be measured at all. When picking a KPI, it is important to ask how much time it will take to gather the data.
- Clear and simple—The best KPIs can be understood without any extra training. The simpler they are, the more useful they'll be for everyone when it comes to optimizing the process.

According to the following considerations the main common losses that apply to COBOTS application OEE (Overall Equipment Effectiveness=Availability x Performance x Quality Rate) are defined:

1. Planned downtime—Due to changeovers, planned maintenance, end-of-arm tooling changeover, etc.
2. Breakdowns and unplanned downtime—Due to equipment failure, unplanned maintenance, etc.
3. Minor stops—Due to misalignment, blockages, safety stops (e.g. due to people entering the workspace), etc.
4. Speed loss—Due to untrained operators, inefficient waypoint programming, misalignment, etc. This category is a major loss for some collaborative robots, which automatically enter a "reduced speed" mode when people enter the workspace or touch the robot. Monitoring and minimizing such events (e.g. by teaching people to only enter the workspace when necessary) is an easy way to improve performance.
5. Production rejects—Due to damaged products, scrap, etc.
6. Rejects on ramp up—Due to scrap caused by changeover, damage, etc.
7. Integration faults (or communication faults, for COBOTs)—The COBOT suffers from brief stoppages due to faults such as errors in machine-to-machine communication or synchronization, misaligned parts, connectivity failure, etc.
8. Lack of use—The COBOT is not being used to its full potential due to lack of training, process optimization issues, poor resource allocation, etc.
9. Inefficiency (poor trajectory planning, for COBOTs)—an un-optimized cell layout leads to inefficient movement of the robot. The robot's paths should be measured and optimized to eliminate this waste.
10. Wait time—The COBOT is unable to achieve its full potential because it is waiting for other processes. This can be due to limited understanding of the COBOT's full potential, bottlenecks or un-optimized steps elsewhere in the process, etc.

Considering that the Wait time and stops are among the major losses, it is important to define the STOP modes of collaborative robots:

- Emergency Stop: This state stops the program and cuts power to the robot. It's usually triggered by an external signal like an emergency stop button. The robot must be manually reset to clear this state.
- Safeguard Stop: Like the Emergency Stop, this state means that the robot has stopped following an external signal. However, it only pauses the program and there is power to the robot. The program will continue either automatically or following a manual reset, depending on the robot's configuration.
- Protective Stop: This stop state is triggered by the internal safety limits of the robot control system. It can only be reset manually.
- Idle: the robot is powered up but no program is running. See the later section on Utilization (KPI 3).
- Disconnected: the robot is powered down or otherwise disconnected from the network. See the later section on Disconnect Time.

After these initial but important considerations, the study bring to the definition (a detailed description) of the 5 top KPIs for the monitoring of COBOTs performances, which are:

KPI 1. Cycle Time: duration of one robot sequence:

Cycle Time = Time Sequence Starts – Time Previous Sequence Started

In general, the more the robot is optimized, the shorter the Cycle Time is. A short Cycle Time (connected to best optimization) is optimal.

KPI 2. Cycles (processes) Completed: How many cycles have been performed by the robot in a particular time period.

KPI 3. Utilization: how long a robot is being used compared to how long it could, theoretically, be used:

Utilization =Times a robot runs a program / Total time

KPI 4. Efficiency: the percentage of time that the robot performs productive work while running a program.

KPI 5. Wait Time: percentage of time that the robot is waiting (i.e. not performing productive work) while it is running a program. We define it as a summation of all individual wait times:

Wait Time = Σ Robot Static Times

In the identification of an application for Collaborative robotics it should be considered that the proper application should better not act negatively on these indicators.

It is important to note that these KPIs are referred to the optimal planned action i.e., for example, if the COBOT supports the operator acting as a continuously adjustable support for the parts, then a high Wait Time can be not meaningful.

All these KPIs are important to be considered in design phase as indicators, nevertheless their application has to be performed only after the effective deployment in the productive environment of the application.

2 HRC APPLICATION DESCRIPTION

Human Robot Collaboration (HRC) creates the possibility to have both the operator and the robot to CoLLaboratE on the same application or in the same workspace. This mixed operation is new and often, standard procedures are not sufficient to design and describe collaborative workcells.

Chapter 2 of this deliverable aims at an analysis of the collaborative applications, workspace and actors in the field, in order to highlight criticism in the definition of the work-application.

The following analysis is focused on the explanation of the elements to be taken into account in design and description phases of the workcell.

Chapter 2 highlights and describe the features to be considered in the description of Collaborative Use-Cases with the aim to improve the collaboration between human and robot in the use cases. The purpose is double: to obtain a description that fulfills the end-user requirements about the definition of new production cells, and to enable the extraction of the references to:

- Functional description
- Human-robot coordination with Roles assignment
- ISO Regulation minimum requirements toward the risk-assessment
- Required hardware and so on.

While identifying, designing and setting up a collaborative workcell it is always fundamental to keep in mind which collaboration level is strictly necessary for the application. For example:

- If the contact or the proximity are not necessary, I can use SMS or SSM mode (lower costs, higher speed…)
- If the proximity and the contact are requested it is necessary to further evaluate the nature of the contact (e.g. HG Hand Guiding to take control of the robot's end-effector; possibility to stop and resume the motion of the robot by a simple touch…)

It is furthermore important to:

- Evaluate which operations are attributed to the Human and which to the Robot
- Determine execution times and saturation (MTM with Robot timing analysis)
- Determine available room
- Analyze constraints (architectural, logistic, quality, ergonomics, cycle time…)

2.1 COLLABORATIVE WORKSPACE (LAYOUT CONSIDERATIONS AND CONSTRAINTS)

Whenever describing a Human Robot Collaboration, it is fundamental to consider the whole Collaborative Workspace.

The complete description of the workplace requires different considerations that will be detailed afterwards, nevertheless this paragraph, describing shortly the concept of the collaborative workplace, aims at introducing the issue and its importance.

The ISO 10218:2 [5] introduces and defines the Human Robot Collaboration as (text in *Italic* is directly from the Standard):

Collaboration is a special kind of operation between a person and a robot sharing a common workspace. It is only:

- *used for predetermined tasks;*
- *possible when all required protective measures are active; and*
- *for robots with features specifically designed for collaborative operation complying with ISO 10218-1.*

In the General Requirements paragraphs it is further underlined that:

Due to the potential reduction of the spatial separation of human and robot in the collaborative workspace, physical contact between the human and the robot can occur during the operation. Protective measures shall be provided to ensure the operator's safety at all times. The following requirements shall all be fulfilled.

a) The integrator shall conduct a risk assessment as described in 4.3 (see Annex E for examples of applications). The risk assessment shall consider the entire collaborative task and workspace, including, as a minimum:

1) robot characteristics (e.g. load, speed, force, power);
2) end-effector hazards, including the workpiece (e.g. ergonomic design, sharp edges, protrusions, working with tool changer);
3) layout of the robot system;
4) operator location with respect to proximity of the robot arm (e.g. prevent working under the robot);
5) operator location and path with respect to positioning parts, orientation to structures (e.g. fixtures, building supports, walls) and location of hazards on fixtures;
6) fixture design, clamp placement and operation, other related hazards;
7) design and location of any manually controlled robot guiding device (e.g. accessibility, ergonomic, etc.);
8) application-specific hazards (e.g. temperature, ejected parts, welding splatters);
9) limitations caused by the use of necessary personal protective equipment;
10) environmental considerations [e.g. chemical, radio frequency (RF), radiation, etc.];
11) performance criteria of the associated safety functions.

b) Robots integrated into a collaborative workspace shall meet the requirements of ISO 10218-1 [4].
c) Protective devices used for presence detection shall meet the requirements of 5.2.2.
d) Additional protective devices used in a collaborative workspace shall meet the requirements of 5.2.
e) The safeguarding shall be designed to prevent or detect any person from advancing further into the safeguarded space beyond the collaborative workspace. Intrusion into the safeguarded space beyond the collaborative workspace shall cause the robot to stop and all hazards to cease.
f) The perimeter safeguarding shall prevent or detect any person from entering the non-collaborative portion of the safeguarded space.
g) If other machines, which are connected or attached to the robot system and present a potential hazard, are in the collaborative workspace itself then the safety-related functions of these machines shall comply, at a minimum, with the requirements of 5.2.

Besides of the specific content of the cited paragraph 5.2 of the ISO Standard, all the above text underlines the importance to describe and plan all the actors in the collaborative workspace.

Considering the ISO/TS 15066:2016 [6] we have:

§ 5.3 Design of the collaborative workspace:

The design of the collaborative workspace shall be such that the operator can perform all intended tasks. Any risks introduced by machinery or equipment shall be sufficiently mitigated by the measures identified in the risk assessment. The location of equipment and machinery should not introduce additional hazards.

Figure 4 describes the concept of the Collaborative Workspace; it is all the space interacting with the Human-robot collaboration. The importance in its description is related to the Safety contents of all the active and passive actors in the workplace; even though not represented in the figure, passive "actors" like architectural elements (columns, walls…) or furniture (tables…) represent a risk, and as such need to be analyzed and included in the Workplace description. Considering the presence of passive risk elements, the ISO standard (10218-2:2011[5]) states that:

The robot system should be installed to provide a minimum clearance of 500 mm (20 in) from the operating space of the robot (including arm, any attached fixture and the workpiece) to areas of building, structures, utilities, other machines, and equipment that allow whole body access and may create a trapping or a pinch point. Where this minimum clearance is not provided, additional protective measures to stop robot motion shall be taken to provide protection while personnel are within 500 mm of the trapping or pinch hazard in a static environment. If there is dynamic motion (e.g. line tracking), special considerations may be needed. (See ISO 13854.)

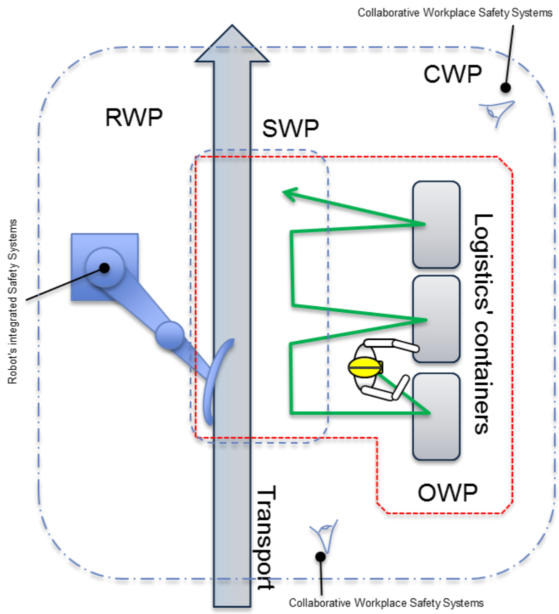


Figure 4: Collaborative workspace detailed

For further considerations about the possible type of interactions, Figure 4 introduces as well the concepts of:

- OWP: Operator's Work Place (zone of movement of the operator)
- RWP: Robot Work Place (robot+gripper+component reachability envelope)
- CWP: Collaborative Work Place (according to ISO/TS 15066 [6])
- SWP: Shared Work Place (zone with where both robot and operator work)

This differentiation is introduced in [13] considering the specificity of the playing actors in order to classify the different possible HRC applications in relation to the collaborative modes defined in the ISO standards.

Referring to Figure 4 above it is possible to make an analysis and classification of the type of collaborative application, considering the spatial superposition, the time simultaneousness of OWP and RWP and the action of operator and robot on the same application or not.

It is important to remember that both the RWP and OWP are envelopes of time dependent functions and as such can be considered as fixed objects (envelopes) or dynamic objects in case of time overlapping.

The description of the use cases requires different levels of layout definition. The most important considerations are those related to the Collaborative Workplace. It is important to consider and highlight every element in the layout description that can influence the collaborative workplace. This analysis and consideration has to be performed recursively along every design phases.

A second consideration to be performed is that in HRC the position of the actors is dynamic; in this framework the layout must obviously consider every movement foreseen for the operator and the robot in any moment of the collaborative operation.

The layout of the workspace can be done as usual with 2D or 3D CAD models, but its full evaluation and dimensioning requires a recursive analysis of the application to be performed together with the task analysis and risk assessment.

2.2 Human operators planning – Task analysis

The Human operator and the robot are the main actors of the collaborative workspace.

For the Human operator different levels of design and analysis are required. It is thus fundamental to include in the analysis different characteristics of the operator's planning that directly or indirectly influence the workcell performances, characteristics and design. The main characteristics affecting or describing the performances of the workcell are:

- the task analysis with relative timings (e.g. MTM Task analysis)
- the type of operation to be performed (e.g. NVAA/VAA see nest section),
- the ergonomics,
- the distance traveled by the operator in the workstation (through the spaghetti chart).

2.2.1 NVAA and VAA

Every operation performed by the operator in its application can be classified in two main groups related to the product value creation chain.

NVAA (Non Value Added Activities) and VAA (Value Added Activities) are two complementary percentage KPIs describing the sum of times over the total execution time of operations that are not creating value or that are creating value respectively.

The value chain contains all the operations performed to create the product's features that the final client is willing to pay for, or that are compulsory for the realization of the product. Other operations are nevertheless necessary for the realization of the product itself without concurring to perception of value.

VAA is thus the sum of the times used for:

- Product transformation (handling, screwing, gluing, welding, assembly …)
- Quality check
- Traceability or similar (those that ensure regulation compliance of the product)

NVAA, on the other hand is the sum of times executed for:

- Logistics (going to pick up sub-assemblies is necessary but not perceived as a value buy the buyer of the final product)
- Waiting (sometimes necessary in case automation and human operator are misaligned in time)
- Walking in general (to pick up tools, parts…)

For a proper productivity planning and optimization the minimization of NVAA in the design phases of the application is necessary.

Figure 5 shows an example of the NVAA minimization process in order to create value by the use of a collaborative robot.

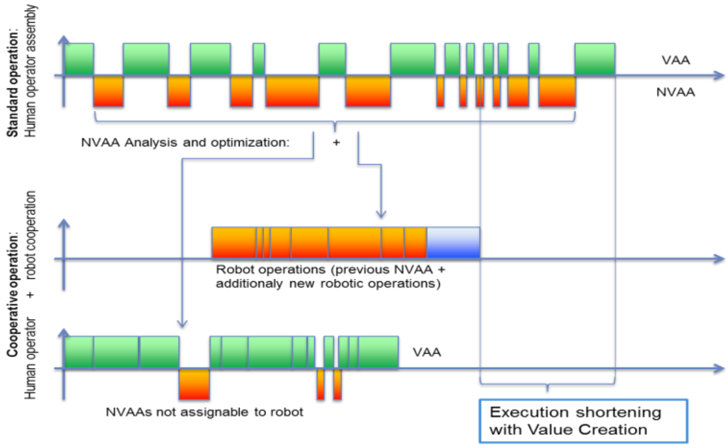


Figure 5: NVAA Analysis for value creation

2.2.2 Ergonomics

Ergonomics is the science that applies the physiological (and psychological) principles to the engineering and design of products, processes, and systems. Ergonomics can be defined like the science of designing the job to fit the worker, rather than physically forcing the worker's body to fit the job [14].

In manufacturing operations human operators can often be exposed to many non-ergonomic movements/actions such as:

- Heavy loads manipulation
- Blind and awkward postures
- Repetitive and cycling movements…

It is a standard procedure to design the workplace in order to reduce the ergonomics workload on the human operators. The aim is to fulfill the goals of occupational health and safety and productivity.

Ergonomics is nowadays faced by a preventive (and on the field) simulation and analysis of the positions, postures and actions performed by the operators. In case ergonomics issues are foreseen, workplaces can be redesigned to eliminate the issue or reduce the impacts to the operators. Proper job rotation planning is needed in order to keep the exposure to ergonomic risk below the acceptable level (defined by the law).

Often mechanical solutions are used to support the operator's activities, such as adjustable seats, workstations and tables, or eventually proper devices and tools can be used such as dampening devices for vibration control, semi-autonomous or passive manipulators and lifters and so on.

The solution to ergonomics issues often represents a cost for the end-user and sometimes, if the optimized solution is not achievable, there is the need to plan job rotation among operators which is expensive and often complicate. COBOTs, thanks to their inherent flexibility, force and safety in interaction with humans, are an optimal candidate for ergonomics improvements, in particular for those workstations in which both management (job rotation) and mechanical solutions are difficult to apply.

Nonetheless HRC and, generically speaking, any form of human-robot interaction (e.g. exoskeletons) introduce some issues in the ergonomics evaluation.

Ergonomics is usually optimized according to standard tools which, up to now, are based on evaluation of a static environment. On the other hand human-robot interaction is intrinsically dynamic. According to this consideration the evaluation of ergonomics has to be made in a different way and, so far, using a non-standardized approach. In this framework the acceptability evaluation performed in the project CoLLaboratE (Task 2.3 and 2.4) can furnish hints to the development of interactive workplaces and applications.

2.2.3 Spaghetti chart

During assembly tasks, the operator has the necessity to walk inside its workcell. These walking phases are classified as NVAA since they are not related to the direct production of the value of the product, but they refer to the workplace organization. For this reason the Spaghetti Chart is a powerful tool in all the Lean Manufacturing methodologies, for the walking phase representation and analysis.

The Spaghetti Chart draws on the layout and quantifies the length of the expected walking path of the operator. As such it allows to highlight un-optimized workcells, wrong disposition of the logistics containers and so on. The Spaghetti Chart has an impact on both productivity (time losses in high NVAA) and ergonomics (km walked per day).

There is no “optimal value” for this KPI since the disposition of logistics and parts depends on many factors and often the Spaghetti Chart Value can be really high even if the path itself is optimized for the specific plant and application. However, the tool is important to optimize the workcell layout, the logistics planning and the working operations. In some cases the Spaghetti charts can show possible risks for the operator of crossing and cross-disturbance.

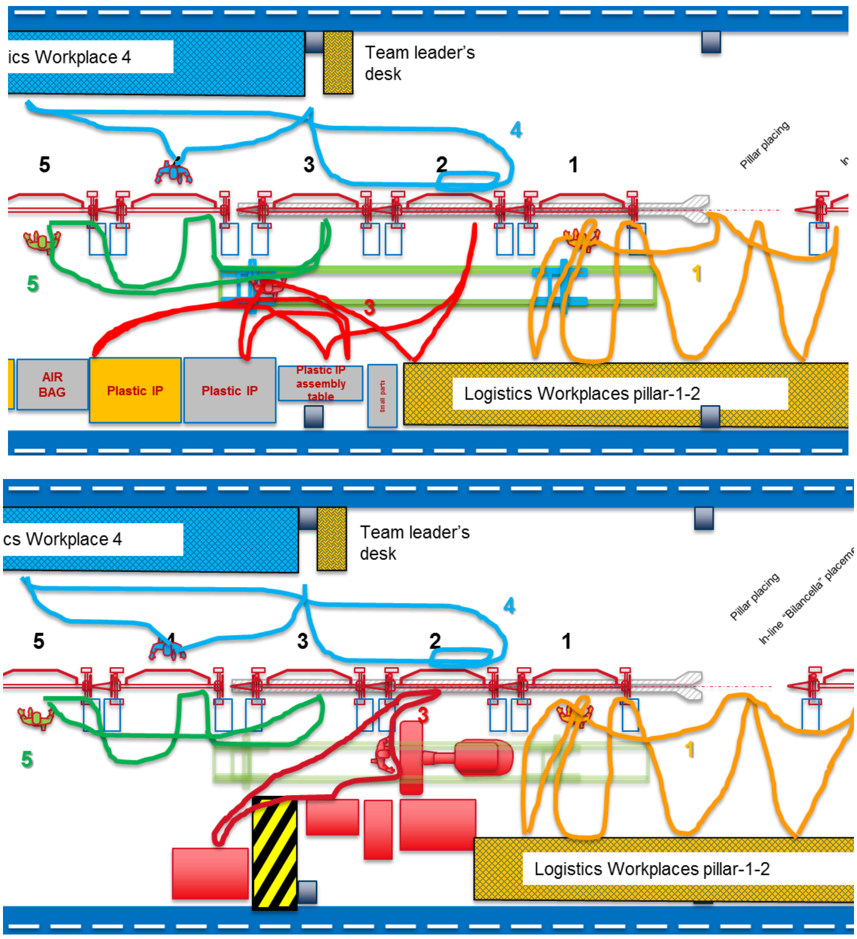


Figure 6: Modification of a Spaghetti Chart before and after planning a collaborative Robot introduction.

In Figure 6 the modification of a Spaghetti Chart before and after planning a collaborative Robot introduction is shown. The COBOT application affects the operator 3 Spaghetti Chart and reduces the risk of interference with operator 5.

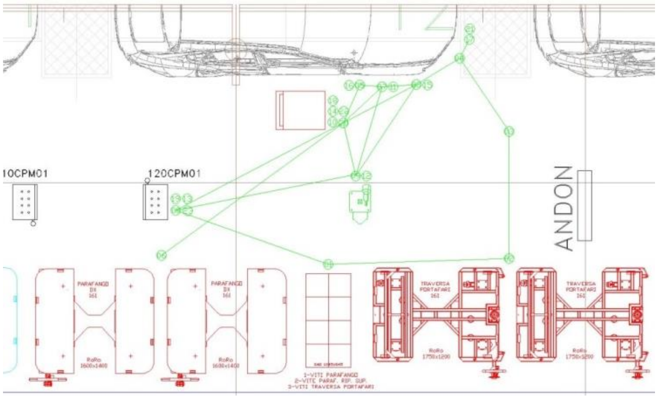


Figure 7: Example of Spaghetti Chart for an operation in automotive Body in White

2.2.4 Task Analysis and MTM

In order to plan the activities of the operator both in terms of time and in terms of required equipment, spaces and so on, a task analysis is required. This task analysis can be performed in different ways and have different content according to the target. One of the most known and powerful methodology for the task analysis is the MTM.

MTM is the abbreviation of Methods-Time Measurement. Methods-Time Measurement means that the time required to perform a specific task depends on the method chosen for the activity. The MTM method was developed 1940s as a system of predetermined motion time used in industrial settings to analyze the methods used to perform any manual operation or task and, as a product of that analysis, set the standard time in which a worker should complete that task. Since then, MTM has been used both as an analytical tool for directly analyzing manual work processes, as well as, a tool for developing standardized building blocks from the MTM basic system (MTM-1). These building blocks are being used to economically describe, quantify and design a wide range of work processes.

In addition to the base MTM, building block systems were developed based on MTM-1 for application in different process types (mass production, batch production and one-of-a-kind and small variable batch production). MTM offers a worldwide uniform standard for businesses to use in describing and quantifying manual work processes. As early as the 1990s, MTM began the gradual transformation from a system of predetermined times to a productivity management system.

Today, the MTM method includes a framework of MTM building block systems used to model the full range of work processes. In addition to the standard MTM, in recent times, ERGO-MTM have been developed in the light of the most recent ISO/CEN standards dealing with biomechanical load; as a consequence the traditional models do not meet the requirements anymore and it becomes mandatory to consider the load generated by the overall assignment of working tasks to a workstation to be compliant with the new ergonomics standards.

ERGO-MTM determines a fatigue allowance (named Ergonomic Allowance), which is applied on the total workstation basic MTM time to allow the necessary recovery periods, enough to keep the biomechanical load within safety limits. The final result is a standard time based on a norm level of performance and a work sequence with a controlled biomechanical load.

From the basis of MTM, many methods can be derived. The basic concept is to have a task analysis tool that associates, to each specific task, other parameters that are useful for the description and representation of the process.

Zanella et Al. [7] used, for the task analysis, a modified MTM-UAS [10] analysis, defined by considering the motion of the robot in parallel with the operator together with its interaction. This kind of representation allows the designer to identify the core tasks (equivalent to task building blocks in the MTM, or eventually grouping even larger time description) according to its characteristics. The description is based on a MTM analysis and a NVAA analysis.

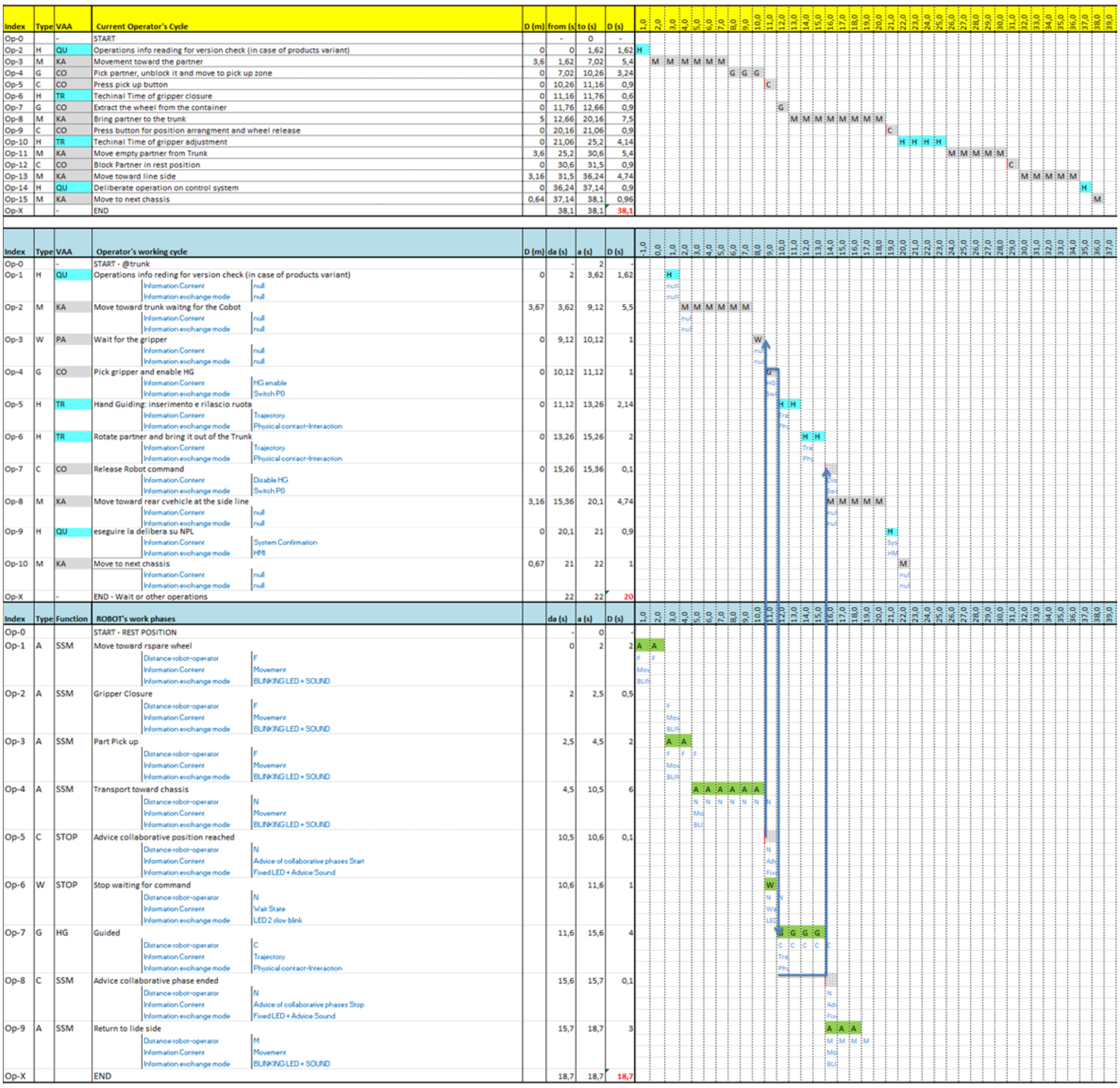


Figure 8: Modified MTM-UAS analysis. Sectors a), b),and c) are explained in the text

The tasks are grouped in order to allow the description of single work phases with a unique characteristic in terms of:

- Same type of NVAA/VAA operation

- Single walking phases are grouped
- Phases of interaction with system (commands, HMI reading…) are defined as single tasks

Figure 8 represents a modified MTM analysis. It is mainly composed by three parts:

a) representing the analysis of the operations as performed by the operator alone;
b) with the analysis of the operations performed by the human operator in collaboration with the robot
c) description of the operations performed by the COBOT.

On the left side of the analysis each operation is classified and quantified, for the operator, according to the MTM analysis (VAA, NVAA and subclasses such as walk – KA, Transform – TR, passivity – PA, and so on); while for the Robot the classification is in term of interaction, wait, hand guiding, handling, automatic and so on, and in terms of cooperative phases according to ISO/TS 15066 [6] (SSM, SMS, HG, PFL) plus the stop condition.

Many information are detailed in the three sections of the representation above. The following figures represent the most important elements. Figure 9 represents section a). It is defined in order to represent manual tasks of the operator in an AS IS mode. In case the operation is at a Green Field, the only part b) contains all the information contained in part a).

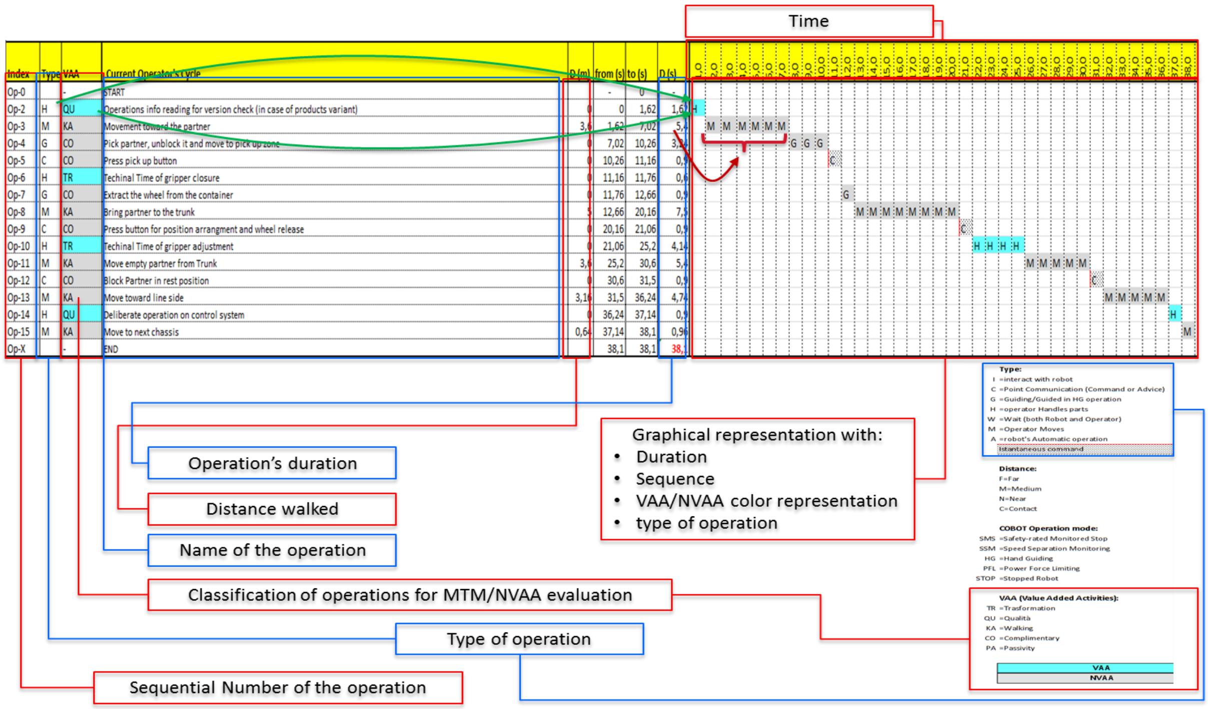


Figure 9: Modified MTM-UAS analysis. Details of Section a)

Figure 10 represents section b). It contains all the information contained in part a) with the specific addition of the information exchange. In HRC the human operator continuously interact with the system through the robot or through other devices. From the functional point of view, the operator needs to have information related to the activities he is performing, or to activities the robot is performing. In section b) the information are those coming from the operator toward the system; in section c) those from the system to the operator.

The definition of the HMI in cooperative systems is fundamental both to achieve enhanced functionality and to evaluate cognitive ergonomics overload. Indeed the operator's environment is filled with stimuli, ranging from:

- Functional interfaces;
- Robot movement information
- Safety rules
- Voluntary information exchange (confirmations, buttons…) and so on.

During every work activity the operator has to face the stimuli coming from the robot that can potentially represent a risk. In this situation the understanding of the Interfaces (both voluntary and involuntary) is fundamental. Furthermore the architectural description of the Use Case can be simplified from the analysis of the interfaces that are needed to fulfill the functional requirements of the workplace.

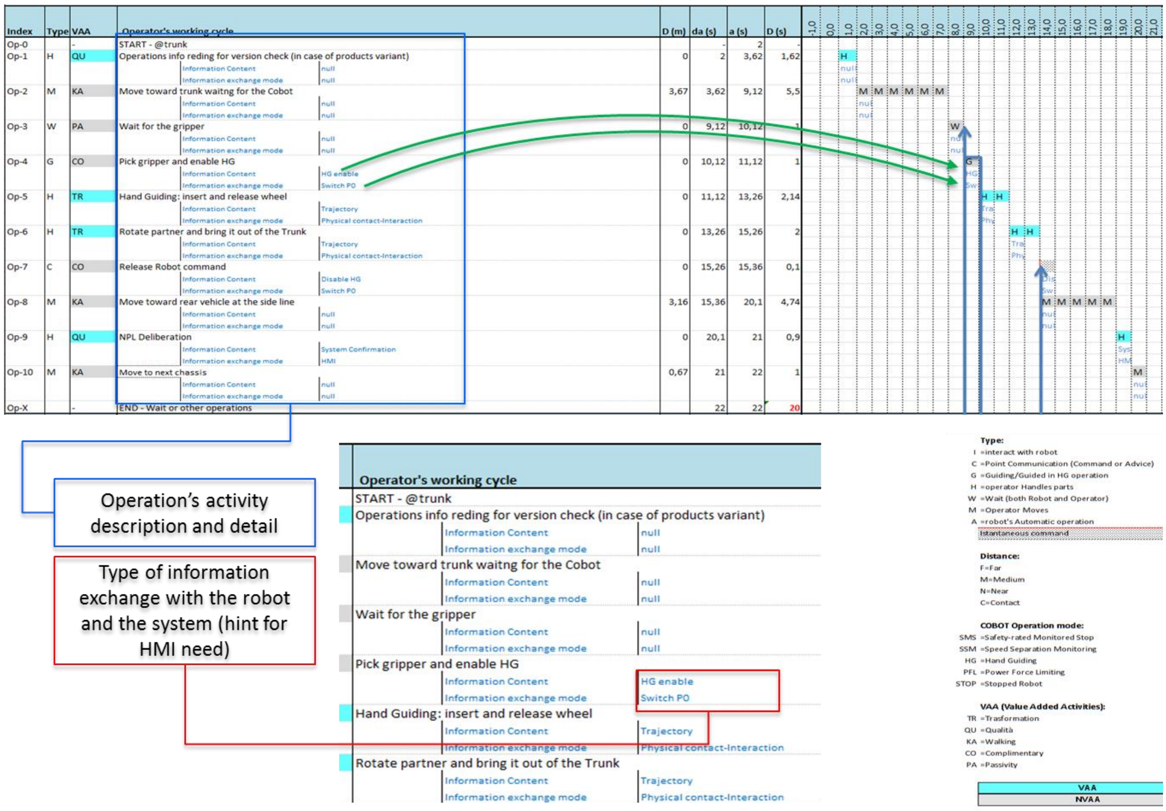


Figure 10: Modified MTM-UAS analysis. Details of Section b)

In Figure 11 there is the representation of section c) that is describing the ROBOT's phases. In addition to previous information there are other information:

- The robot operative modes according to ISO 102018:2;
- The relative distance
    - F= robot and operator cannot touch each other;
    - M= Operator can enter Robot zone easily;
    - N= Operator is in the Robot zone;
    - C=operator and Robot are in contact like for Hand Guiding
- The information from the robot to the operator

Finally section b) and c) are connected by arrows that indicate processes starting from the robot or the operator that needs interaction with the cooperator and go back as soon as the operation is closed.

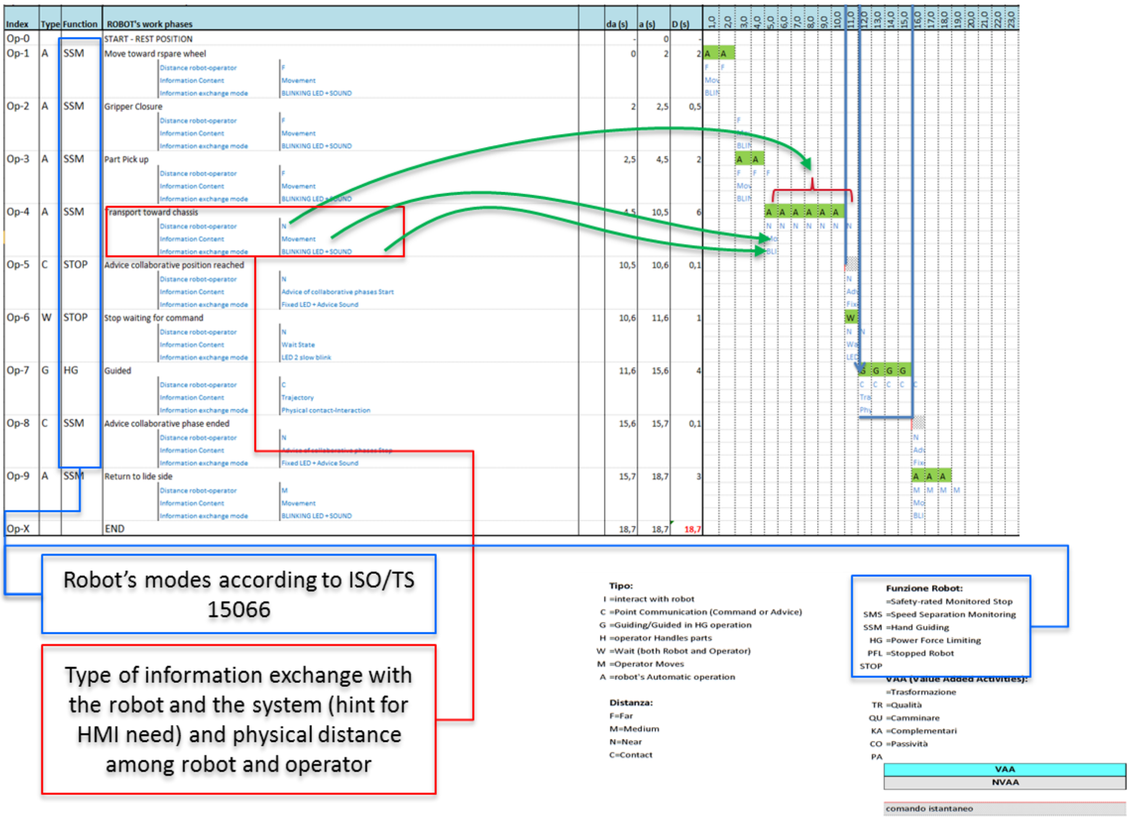


Figure 11: Modified MTM-UAS analysis. Details of Section b)

2.3 HRC Collaborative Operating Methods

The ISO standard ISO10218:2 [5] introduces and details the concepts of the four Collaborative Operating Methods.

Any application defined according to the ISO standards have to be defined according one or more of these methods, introduced shortly in paragraph 1.1. Their functionalities are defined to cover all the needed applications in a collaborative environment. As described in the paragraph 2.2.4, the used task representation contains, for every task, a reference to the collaborative method used in the specific task; this is because the ISO itself details hardware and functional requisites for each collaborative method. In this paragraph the collaborative methods will be detailed further.

The four methods (described in details in the paragraph 1.2) are:

a) Safety-rated Monitored Stop (SMS);
b) Hand Guiding (HG);
c) Speed and Separation Monitoring (SSM);
d) Power and Force Limiting (PFL).

2.4 Robot and related hardware identification

2.4.1 COBOT

Production of COBOT started around 2008 with the Universal Root UR5 and exploded in 2016 after the publication of the ISO/TS15066. Up to now many producers are on the market and the availability of robotic solutions and their equipment is high. The choice of the best COBOT for any specific application has to be done according to many factors. First of all the main factors should be those related to the application feasibility:

- Payload
- Reach
- Speed/acceleration
- Precision
- Repeatability, and so on.

The above factors are the same as those usually considered to identify any Robotic arm; considering the intended application is collaborative these characteristics are important. First it is important to remember that the robot has to fulfil ISO 10218-1 (requirement) that is to be *Safety category 3, performance level PLd*.

Secondarily, HRC specific features can be simplified, when not directly embedded in the control, by some robot's characteristics. For example in case of PFL operations a robot with an integrated and advanced force control already satisfy the sensor requirements (e.g. a KUKA LWR iiwa with its integrated 7 torque sensors – one per joint). Other cases of interest are the TM (OMROM) with integrated 2D camera, the COMAU AURA (high payload robot: 170kg) which is equipped with a capacitive and piezoelectric skin for SSM strategies and for advanced contact detection which are necessary in high loads.

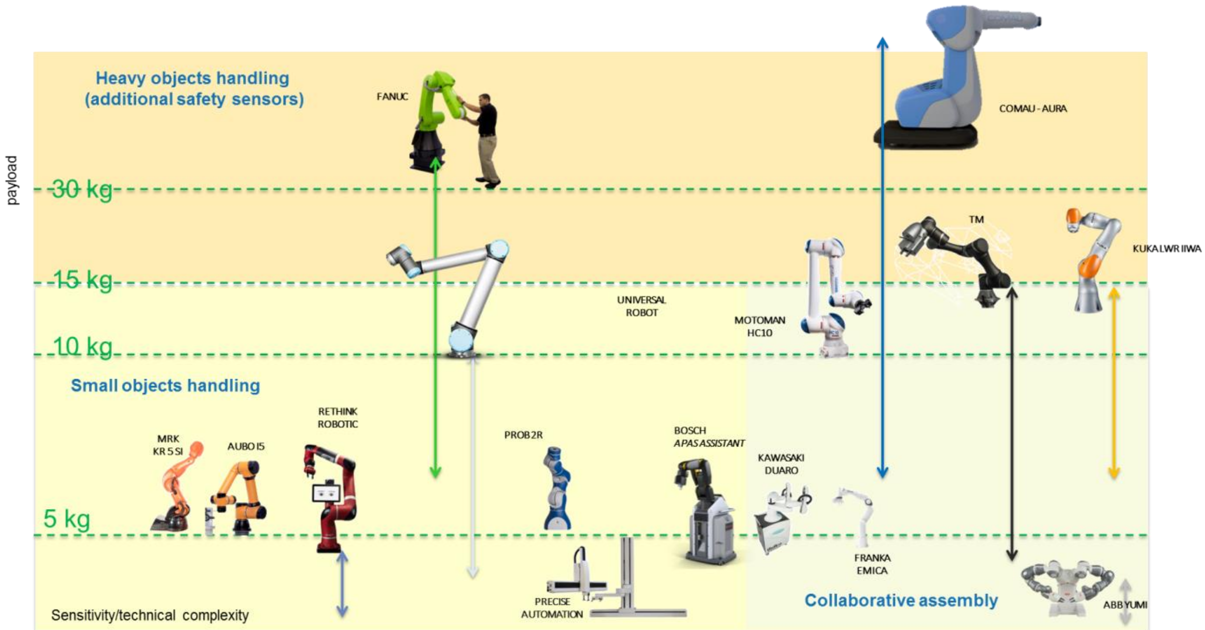


Figure 12: representation of commercial COBOT scenario (2018)

The design of the robot is important as well: new collaborative robots (e.g. UR e-series) have a design that, besides of the rounded shapes to reduce impact generated pressure, is inherently anti-scissoring.

Last it is important to consider the programming simplicity: indeed many new COBOT maker have started to design robots with an extremely simplified programming approach (e.g. the FRANKA Emika or the TM). This approach is targeted to a simplified use especially in SMEs that can't afford a professional programmer as a fixed resource. It has to be underlined that anyway the programming of "safety" critical SW should be made professionally and the safety functions should better be listed in the Risk Assessment itself. The simplified approach is thus normally applied only to lower payload COBOTs so that any contact risk is automatically reduced. Higher payload robots have a standard programming approach.

Figure 13: Word cloud of COBTs' keywords

2.4.2 End-Effectors

ROBOTs are party completed machinery, as such they functionality require an end-effector that, applied to the robot's flange, performs the operation itself. According to different applications, robots can use different end-effectors that enable it to perform specific functionalities; for example:

- Cameras for vision (2D, 3D; photometric, profilometers, etc.);
- Welding guns
- Gluing devices;
- Grippers and so on.

An interesting new market is born practically in concomitance with the exit on the market of the first commercial COBOTs by Universal Robots: the flexible grippers. Flexible grippers are a family of simplified industrial manipulator optimized for flexible manipulation of low payload parts and they are perfectly fitting with standard, simple collaborative applications. In the last years, new specific grippers have been placed on the market specifically for collaborative applications (SCHUNK, ZIMMER). They are equipped with pressure sensors, presence sensors and other features that simplify the collaboration with men.

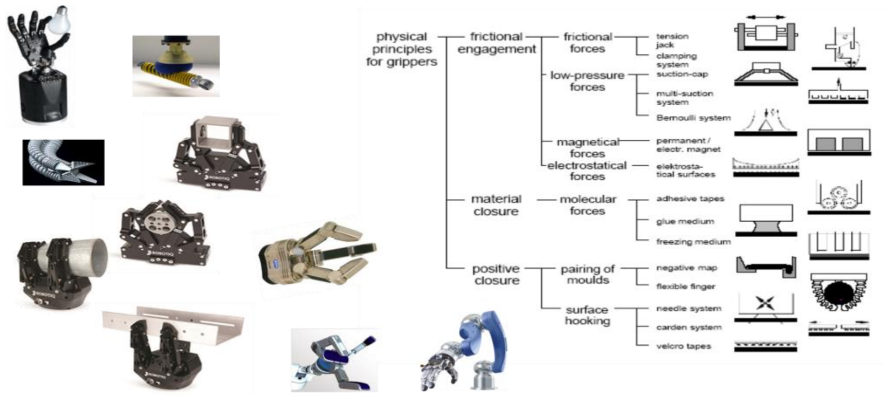


Figure 14: Flexible manipulation grippers and gripping principles

Besides of the commercial availability, in any HRC application the expected functionality brings to the definition of the required end-effector. In HRC applications it is always fundamental to design or "dress" the gripper in such a way that no sharp edges are present; furthermore clamping phases should be properly monitored so that the operators cannot put their hands in the mechanisms or below the manipulated weight in any moment (crushing or shearing risks).

The design and description of the end-effector is fundamental since, as a consequence, safety measures are set.

2.5 Safety System

Safety in a collaborative workcell is seldom achievable only through the use of a collaborative robot. Though the COBOTs have inherent tools and characteristics that reduce the risk of harming the operator a full Risk assessment must be done. Elements like the end-effectors, the parts transported by the robot (if any) or the processing tools must be analyzed as well.

The complete task analysis highlights elements and phases when the interaction is really close, and in these cases a proper and complete planning of the workcell is required. When the distance among the operator and the robot gets too short, then a proper collaborative method has to be identified according to the desired functionality. As stated in the previous paragraph, each of the collaborative methods involves a set of hardware requirements. For example SSM requires for sure a sensory system to detect the distance between the operator and the Robot. This system has to fulfill all the functional requirements of the ISO standard, but in theory it can be obtained both by vision systems and by capacitive sensors on the robot. The above example is representative of the inexplicit hardware requirements that are necessary for the safety of the workstation.

From the ISO 10218:1 [4] all the devices used for safety need to have a control category 3 with Performance Level d besides of the safety's strict requirements about connectivity and network architecture. The identified protocol needs to be redundant and with a limited latency in every information exchange (e.g. PROFISAFE is safety standard protocol in PROFINET applications). The PLC used for safety need to fulfill specific requirements and are usually special dedicated devices.

This deliverable doesn't have the ambition to completely describe the requirements of HRC hardware and SW, but to furnish a comprehensive introduction to all the required features in the HRC applications. Safety, in Human-Robot Collaboration is critical due to the close interaction of Human operators with Robots. The requirement to have a Performance Level d as a matter of fact is derived from the risk of heavy injuries or death and as such it implies high reliability hardware. Every work-application and use-case has to be described in terms of Safety devices and their interconnections.

2.6 Interactions and Logistics

One the characteristics that potentially hinder the feasibility of a collaborative work-cell is the design of the logistics. Most of the workcells need a logistic flow. In HRC robots can perform applications of:

- Manipulation (cooperative or in space sharing);
- Process (welding, gluing…)
- Quality control (vision systems for defect detection, bar code reading and so on)

In all the above cases a product must be present on the line, to be manipulated, processed or viewed. The Robot obviously needs to know where the product is located with a precision which is determined by the process itself. The following requirements are fundamental for a proper processing of a part:

- Precision and repeatability (in 6 axes, i.e. orientation): positioning requirements from 0.05 to 0.5 mm.
- Accessibility: whatever the process, the part need to be accessible for the robot's tool
- Availability: the part has to be available when the robot needs it, and so on.

The Organization and choice of the logistic organization is thus obviously fundamental for a proper automation of the processes. It is always important to define the way the parts get in the process and how they need to exit from the process. HRC sometimes is used to support the robot in case of error that can block the application to run (e.g. to support the bin emptying of the final parts in a Bin Picking application). The following figure represents a series of transport devices.

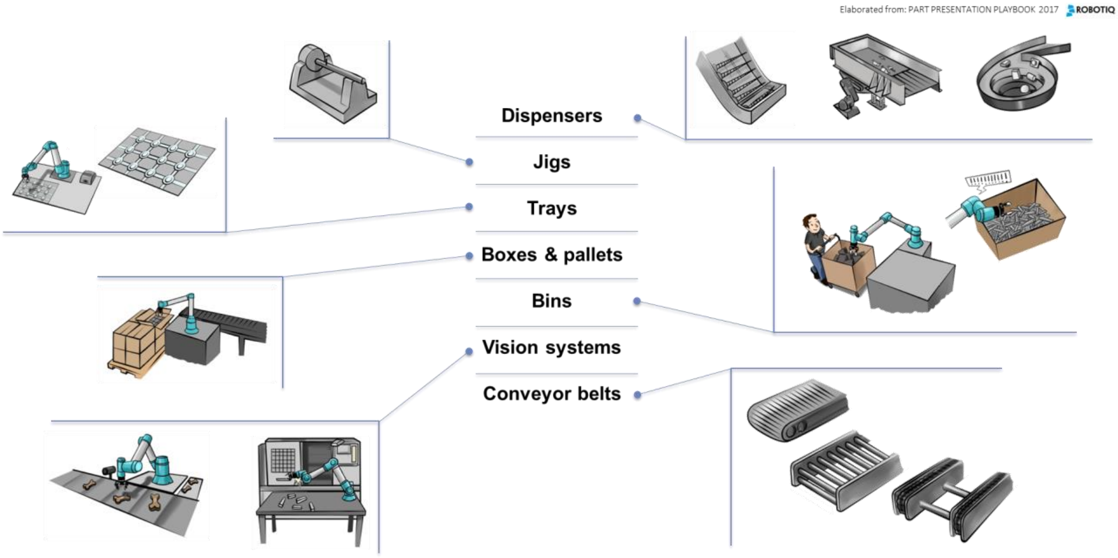


Figure 15: Parts presentation

Another important point to be considered is the amount and dislocation of logistic containers for the operator: in many cooperative assemblies (e.g. the automotive processes) the final product runs on a central conveyor, while the sub-assemblies arrive at side line in gravity shelf or other kind of containers. In the collaborative phases both the robot and the operator can pick up parts from the logistics and place them on the finished part. The position of the logistic containers can ease the application, both for robot and operator, or it can hinder it, causing non reachability, too long spaghetti chart and so on.

2.7 Interfaces requirements & Information exchange

Finally it is fundamental to define the connectivity of the Robot with its world. Inside the workcell many interfaces are required to achieve a proper working ability. In standard manual cells, the system acts often at a too high level to be conveniently aware of all the events occurring in the workcell. The complexity of the motion of the operators and their unpredictability is such that the system cannot perform any automatic monitoring of the tasks. In order to have a proper feedback from the operator, often the system relies only on voluntary feedbacks coming through an HMI (Human Machine Interface). For a very limited set of operations (e.g. screwing in automotive lines) the tools are "intelligent" and give a feedback of the performed operations (torque profile in time, number of turns, pressing force, time profile in absolute time…). Besides these kind of "intelligent" tools are expensive and are normally used only when more restrictive quality or traceability requests are done.

In the Human-Robot Collaboration, on the other side there is the new "robot" element that can interact with the operator. The Robot is inherently a connected machine: normally most of the operations are programmed inside the robot controller which is interfaced to the cell or line's PLC. This situation creates a normal and complimentary bridge for the information to the higher level Manufacturing Systems like the MES (Manufacturing Execution System).

On the Human side, the robot needs to have a certain level of awareness of the situation in order to fulfill the safety requirements of the workcell.

For HRC applications it is possible to highlight the minimum level of requirements that are:

- SMS systems require the presence of a safety sensor (environmental sensing) in order to stop the motion;
- SSM systems need to know the position and speed of the persons in the workzone to regulate its own speed in real time.
- In HG the robot need to have a specific handle capable to detect the action request and to understand whether it is voluntary or not;
- In PFL the robot need to have an advanced and safe force feedback in any time.

Besides of the functional specifications, the interaction with the robot generates new risk situations that can distract the operator. Proper signaling of the working conditions (besides being requested by the standards in same specific cases) are useful for the operator to act safely and properly. The robot in the workcell is in a central position to manage most of the knowledge flow related to the system defined in the workcell.

It is possible to separate three main level of information:

1. high level interaction toward logical fluxes of plant management;
2. workcell management, coordination and know-how of the workcell; awareness of the environmental situation (number of operator, position…)
3. Operative information which can be divided into:
   a) Devices information (process sensors…)
   b) Operator information (what he is doing, when…)

The above fluxes are represented synthetically in Figure 16.

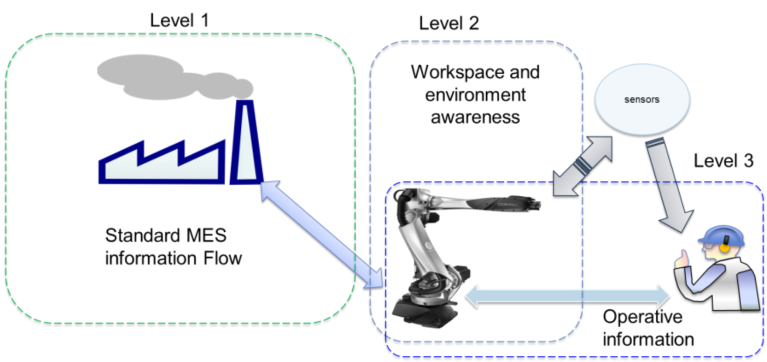


Figure 16: High level information flux

For the specific purposes of the HRC the information flow acts around the workspace and can be detailed as:

- Safety sensors for workspace awareness
- HMI for communicating with the operator; these are bidirectional HMI and can be acting at visual, acoustic or haptic perception level
- Sensory devices and actuators for process specific purposes.

All these information flow is fundamental for the proper execution of the activities and thus needs to be properly represented and defined. As for the flow towards the operator, it is important to highlight that the operator is already concentrated onto its own operations and for the detection of the robot's motion (to avoid collisions). This situation can be already generating cognitive stress; for this reason the optimization of the HMI with the operator should take into account procedures to lower the risks related to cognitive ergonomics.

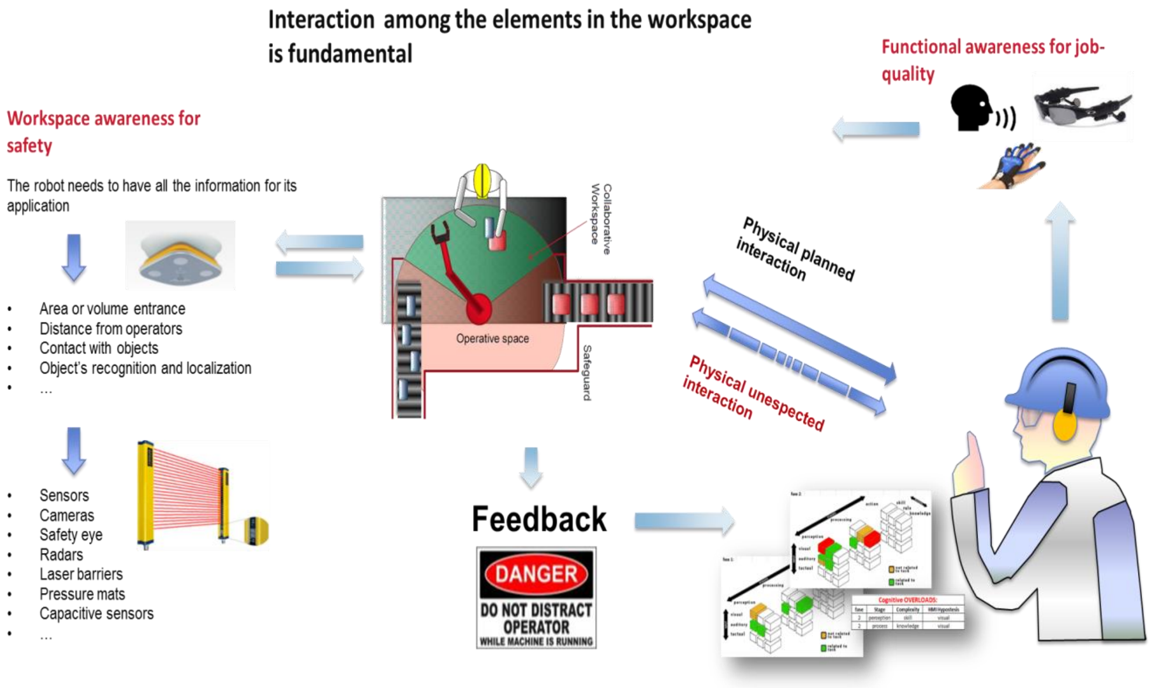


Figure 17: HRC Information flow around the Collaborative Workplace

2.8 FUNCTIONAL ANALYSIS FOR ARCHITECTURAL FEATURES IDENTIFICATION

System architecture describes its components and their interaction that is fulfilling the required functionalities. The overall architecture of the CoLLaboratE system (that will be presented in Deliverable D2.2 M12) will be derived by several interconnected modules that will be defined as software or hardware elements with established relationships between them. Thus, the architecture is modular, enabling the user to utilize each functional element.

The functional view of the system's architecture defines the components that provide its functionality. The view describes the functional structure of the system, demonstrating how the system performs the required functions. The functional structure of such view, as defined by Rozanski & Woods [19], typically contains interfaces, connectors, external entities, and functional elements:

Interfaces are specifications, defining how the functions of a component can be accessed by other components. An interface is defined by the inputs, outputs, the provided operation and the interaction needed for the operation.

External Entities are other systems, software programs, hardware devices, or any other entity the system interacts with. These are described as dependencies to other systems or components.

Functional Elements are well-defined components of the system that have particular functionalities and expose well-defined interfaces that allow them to be connected to other components. A functional component can be a software module, an application, a data collection, or even a sub-system.

A basic step towards the definition of the system components is the specification of its functional requirements and their assignment to specific Functional Elements. In order to derive these requirements, we employ the collected User Requirements and apply the Volere Methodology.

More details will be presented in deliverable D2.2 on System Architecture (Preliminary Version M12). However, in order to provide a broader understanding of the utilization of the extracted User Requirements and their role in deriving the system requirements and shaping the system architecture, a short introduction to the Volere methodology is presented below.

2.8.1 Volere methodology and template intro

A number of system requirement specification methodologies have been proposed over the past, with each one introducing different approaches for the categorization of requirements and focusing on a specific type of applications. Although some of these methods have been compared in relevant literature [20] , no wide consensus is reached on, regarding the selection of the optimum methodology based on the needs and the application area of a project.

The first version of the Volere Requirements Specifications template was released in 1995 and focused on a highly detailed structure that tries to integrate the widest possible spectrum of requirement categories. The Volere template covers the drivers, constraints and the dynamically arising issues of a project. In addition, based on the Volere template the system requirements are separated into two fundamental categories, functional and non-functional. The Functional Requirements describe the desired functionalities that the project should have and how they should be connected in a complete useful final product. The Non-Functional Requirements on the other hand describe the desired properties of all the components of the system such as their performance, efficiency, and usability.

The main advantage and quality that separates the Volere methodology over its alternatives is the detail in which the functional and non-functional requirements are identified. In this way, the Volere template facilitates the organization of the requirements thorough understanding with regards to the project. In addition, Volere offers a formal template for the collection of the requirements in tabular format through its “requirements shell” (also called a “snow card”). The suggested template is illustrated in Figure 18.

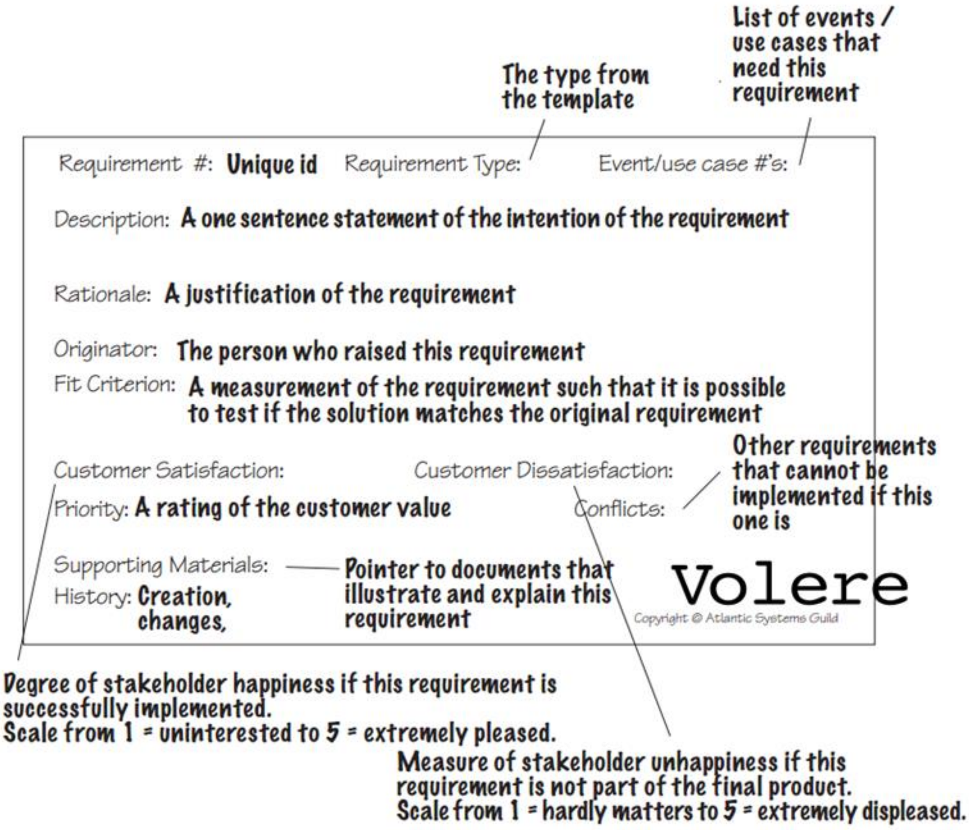


Figure 18: Volere Requirements shell as a guide to writing each atomic requirement

For the description of each specific requirement that belongs to each one of the categories listed above, a tabular template was created based mainly on the Volere requirements shell, after applying the following modifications:

- Name. This field has been added in order to provide in addition to the ID field, a short name that describes the specific requirement in human readable format.
- Constraints, which describes potential constraints / conditions for the requirement to be executed.
- Difficulty, which indicates the level of difficulty for the implementation of this requirement (estimated from a technical point of view). Difficulty ranges on a scale from 1 (=low difficulty) to 5 (=extreme difficulty).
- Actors, indicates either those persons or things that interact externally with the system or one of its components.

Removal/replacement of fields:

- Supporting materials: This field has been also removed because the majority of the documents that are related to requirements will be subjected to IPR.
- Originator (the person who raised this requirement), this field has been replaced by the Author field (the owner of each recorded requirement).
- History this field has been replaced by Revision (indicates versioning).

The final template followed for the definition of a system requirement for CoLLaboratE is presented in Table 4.

Table 4: Template for defining a system requirement.

ID	A unique identifier.
Name	Title of the requirement.
Requirement Type	Functional / Non-functional
Description	A requirement must be described with as much detail as possible. If necessary, an example has to be added.
Rationale	A justification of the requirement.
Fit Criterion (Measurable)	The term measurable refers to the ability to identify if the requirement has been met at the final stages of the project, and after the system has been constructed. In other words this means the tests which must be performed in order to verify whether the requirement has been addressed.
User satisfaction	Degree of stakeholder satisfaction depending on the successful implementation of the current requirement (Scale from 1=uninterested to 5=extremely pleased). Definition for every category of involved stakeholders (worker, production manager, system technician, researcher).
User dissatisfaction	Degree of stakeholder dissatisfaction if this requirement is not implemented (Scale from 1=hardly matters to 5=extremely displeased). Definition for every category of involved stakeholders (worker, production manager, system technician, researcher)

Priority	The requirement is ranked according to the value that distinct categories of users attach to it (worker, production manager, system technician, and researcher). (Scale from 1=low priority to 5=highest priority).
Conflicts	Description of any relation of the current requirement with previously described ones. Special attention to conflict with other requirements whose implementation is blocked by this one.
Constraints (Attainable)	An attainable requirement will usually answer the question: “How can the requirement be accomplished?” Hence, here we explain any constraints / conditions for the requirement to be executed.
Difficulty	Level of difficulty for requirement implementation (estimation). (Scale from 1=low difficulty to 5=extreme difficulty).
Actors	An actor is someone or something outside the system that interacts with it or with one of its components (primary actor). If the actor is interacted by the system or one of its components is a secondary actor.
Author	The owner of each requirement that was recorded.
Revision	This section lists when a version of the requirement was created.

Thus, from the user requirements collected by the use case analysis (Chapter 0), a first level description table will be compiled for each system requirement, where user satisfaction and dissatisfaction should be reported, along with initial description, involved actors, priority for the different actors, etc. These tables will further be processed in Task T2.2 and their final form will be used for deriving the system's modular architecture that will be presented in deliverable D2.2.

2.9 User Requirements

The term ‘user requirements’ is used to describe the high-level abstract requirements whereas ‘system requirements’ means the detailed description of what the system should do. User requirements and system requirements may be defined as follows:

- User requirements are statements, in a natural language plus diagrams, of what services the system is expected to provide to system users and the constraints under which it must operate.
- System requirements are more detailed descriptions of the software system's functions, services, and operational constraints. The system requirements document (sometimes called a functional specification) should define exactly what is to be implemented. It may be part of the contract between the system buyer and the software developers. [25]

2.9.1 Methodology of formulation user requirements

In order to have a comprehensive analysis of the use cases, a mixed methodology, a combination of qualitative and quantitative methods, is applied [15]. The qualitative perspective offers an understanding of the users' perceptions by considering non numerical data such as text, pictures or videos [16], while the quantitative approach uses numerical values, used here to quantify the data and validate choices [17]. Gathering requirements can take multiple forms. Therefore, user requirements formulated within CoLLaboratE should answer the following questions, retrieved from [18]: (a) In what environments must the robot operate? (b) Are there any dangers, which the robot must react to? (c) What interaction is required with the environment? (d) Does the user require sensory feedback from the environment? (e) Is it necessary to manipulate the environment? (f) What interaction is required between the user and robot? (g) What is the workload of the user? (h) What training is available? (i) What are the mission requirements? (j) How accurate must it perform its operations? (k) What functions must the robot perform? (l) Are there any optimization criteria? These questions should represent the minimum of received information, as other areas of interest might also be identified as the outcome of the study. To facilitate the use case interviews, sub-questions were prepared (see Appendix A). The process of formulating user requirements consists in data collection, analysis and interpretation, as presented in Figure 19.

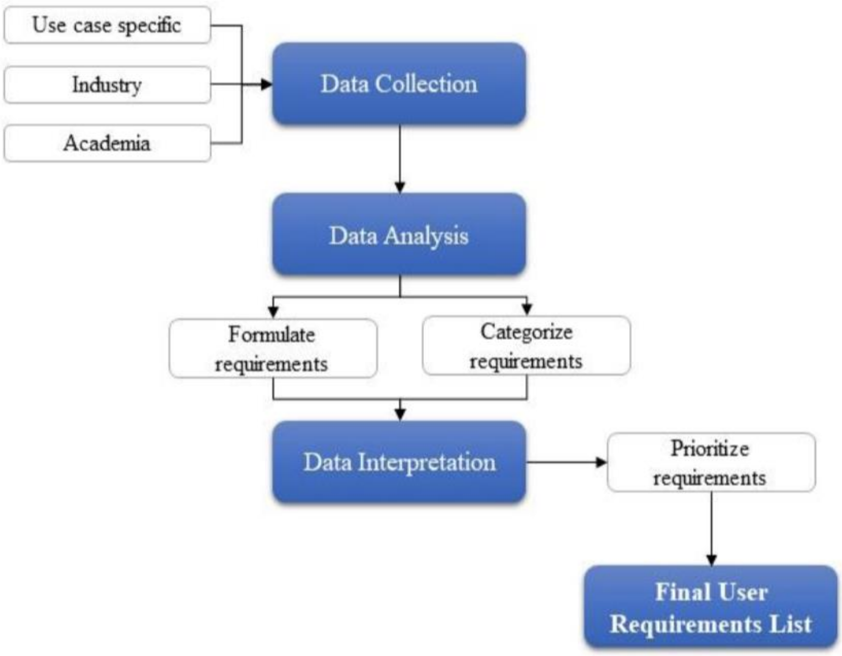


Figure 19 Process of formulating user requirements

The data collection within CoLLaboratE includes interviews with use cases representatives to document their needs, conducting semi-structured interviews with three predefined areas of interest, allowing to facilitate open discussions. The questions used for this interview are presented in Appendix A. The first focus area is to identify the problems with the current situation, how problems are solved in each of the use cases and what other problems there are which can be relevant for the technologies developed within CoLLaboratE. The second focus area relates to the user environment, e.g. who the end-users are, including their background information, and what kind of services would they need to use these technologies. The last area of interest is to discuss non-functional requirements such as expectations about performance, maintenance, support, security, installation, safety and others. The interviews are planned for two hours for each use case. Besides the interviews, the use case representatives are asked to provide text, pictures and video files of the use cases, in order to better observe and understand their applications. Since these methods help in understanding and documenting the use cases, a more general approach is adopted as well, to collect information from other representatives of industry and academia. A survey with 15 questions (Appendix B) was prepared to gather insights about collaborative robots. It focuses on the type of organization the subjects represent and depending on this, which would their needs be if they were to adopt collaborative robots to automatize their processes. A sample of minimum 20 subjects is expected to answer this survey.

Upon collection, the data will be analyzed with the purpose of formulating a list of user requirements and categorize them as use case specific and / or general, which can be applied to all use cases. Furthermore, all the results will be integrated in a prioritization matrix and ranked based on multiple criteria. Thus, the matrix considers three ranking perspectives: end-users, customer and development, each having three ranking criteria, yet to be decided on. A 1 to 5 Likert scale will be used and an average for each identified user requirement will be calculated. Based on these perspectives, a prioritization of requirements will be possible, based on the value for the end-user and ease of development, by also considering the value for the customers. This is important as it will facilitate discussions when transforming the user requirements into system requirements.

2.9.2 Stakeholder Questionnaire

Since these methods help in understanding and documenting the use cases, a more general approach is adopted as well, to collect information from other representatives of industry and academia. A survey with 15 questions (Appendix B) was prepared to gather stakeholders' insights about collaborative robots. The target audience is stakeholders such as industrial experts, end-users and experts from academia working on the objectives of the CoLLaboratE project. The questionnaire focuses on the type of organization the subjects represent and depending on this, which their needs would be if they were to adopt collaborative robots to automatize their processes. A sample of minimum 20 subjects is expected to answer this survey to be able to match the results with the analysis of the CoLLaboratE user requirements.

3 CoLLaboratE Use Cases

3.1 Challenge 1: Performing Car Starter Assembly

The subject of the collaborative process is the assembly of a part of the car starter for the manufacturer Renault. This part of the process comprises inserting copper sliding rings into metal pallets, which are then transferred to the molding machine. Currently, the process of inserting sliding rings into the pallet is performed manually and is considered hard to automate.

3.1.1 Use case general description and introduction

The operator who inserts sliding rings in a pallet also performs other tasks on the same and other production lines. The sliding rings are distributed on a plate with random position and orientation, see Figure 20center. During the insertion into the pallet (see Figure 20right), the worker has to take care for the correct orientation of the contact 'wings' of the cooper rings. The process is demanding due to the high flexibility and elasticity of the sliding rings. Previous attempts of automation failed for two reasons: 1) it was not possible to grasp the sliding rings, because they are often stuck together on the transport plate; 2) it was not possible to assure the required success rate of the insertion due to the flexibility and elasticity of the rings.

Figure 20: Left: Finished part after mold injection. Center: Sliding rings on a transport plate. Right: Sliding rings correctly inserted into the pallet.

The vision of the project is to develop a robotic system that will assist the worker or even replace the worker when he will not be present (see Figure 21right). Therefore, the worker and the robot will be both capable of executing same operations, the work sharing will be assigned dynamically. The task of the worker will be to a) grasp the rings from the transport pallet and put them on the table, and b) to supervise the assembly and correct it if necessary. The worker will often leave the cell, since he will have to supervise also other production cells. Insertion of a slide rings can be divided into three phases: 1) grasping the part from the table, where the part position is not defined in advance 2) rough insertion of the part and 3) fine adjustment of the part. The initial learning will be accomplished by observing humans using technology developed in WP4. From this data, the system will generate approximate trajectories and probabilities associated with the confidence of the captured trajectories. In the next learning stage, the operator will manually guide the robot along this trajectory and perform fine tuning (WP4,). After the learning, the robot will start with exploitation phase and autonomous refinement of the assembly trajectory (WP4). The objective for learning will be to minimize the contact forces and torques and to successfully accomplish the assembly task. Success of the assembly operation will be determined from a) observing whether human operator had to correct the assembly; and b) from vision sensor, where the system will learn from the human feedback. Grasping deviations will be detected using precise RGBD sensor. In order to generalize to the different grasping situations, we will apply deep Q learning algorithms, which will map RGBD image to the assembly policy. The benefit of this cooperative automation will be in a shorter cycle time. Moreover, the system will become more and more autonomous and hopefully would need less and less assistance from humans. Note that in a modern production, humans normally assist more than one work cells and it is less likely that humans would tightly cooperate with humans all the time. This use case will be the pilot case for many similar work-cells in "Kolektor" factory. Although "Kolektor" is not an SME, there are plenty of work processes that do not justify fixed automation, as this would elevate the production cost in low-batches production and increase the setup time. By applying reconfigurable hardware elements, the same work cell will be used in many operations that are currently performed manually. This concept has a great dissemination potential to many tasks in SME and craft production.

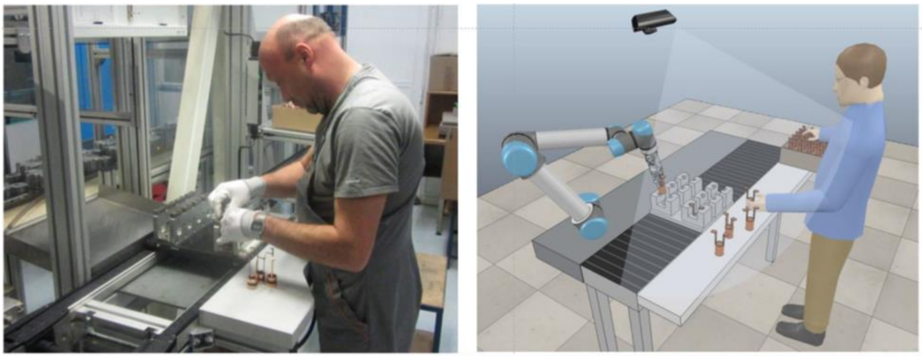


Figure 21: Left: Current state of manual assembly. Right: Automated assembly in a collaborative way

3.1.2 Use case general description and introduction (CO)

The production line in question for the use case is in an active production environment in Kolektor ASCOM d.o.o. A general overview of the entire production cell (line) layout with the area planned for the Challenge 1 implementation is shown on the figure and described in the following paragraphs.

Table 5: CoLLaboratE Challenge 1 layout description

Nr.	Description	Note
1	Open area accessible to workers	*Challenge 1 implementation area*
2	Enclosed production cell area	*Safety feature for robot manipulation*
⓪	Worker / operator	
①	Injection molding machine (IMM)	
②	Feed robot with a customized gripper and 6DOF – feeding the IMM	
③	Pallet (empty) returning to the open area	
④	Tray of copper inserts	
⑤	Box of finished parts	*Once the box is full a new empty one is stacked on top of it.*
⑥	Pallet on the refilling station	*Stop position*
⑦	Circular conveyor belt track	
⑧	Pallet on the feeding station	*Stop position*
⑨	Finished products on a cooling conveyor belt	
⑩	Finished products, cooled and ready for packaging	

The workers task is to place 8 semi-finished copper inserts (4) into the pallet with specialized fixtures for parts. These fixtures are designed so that they hold the geometry of the part so the feed robot (2) can transfer them to the injection moulding machine (1). Once full the worker presses a button which triggers the pallet to move forward on the circular conveyor belt track (7) to the buffer area.

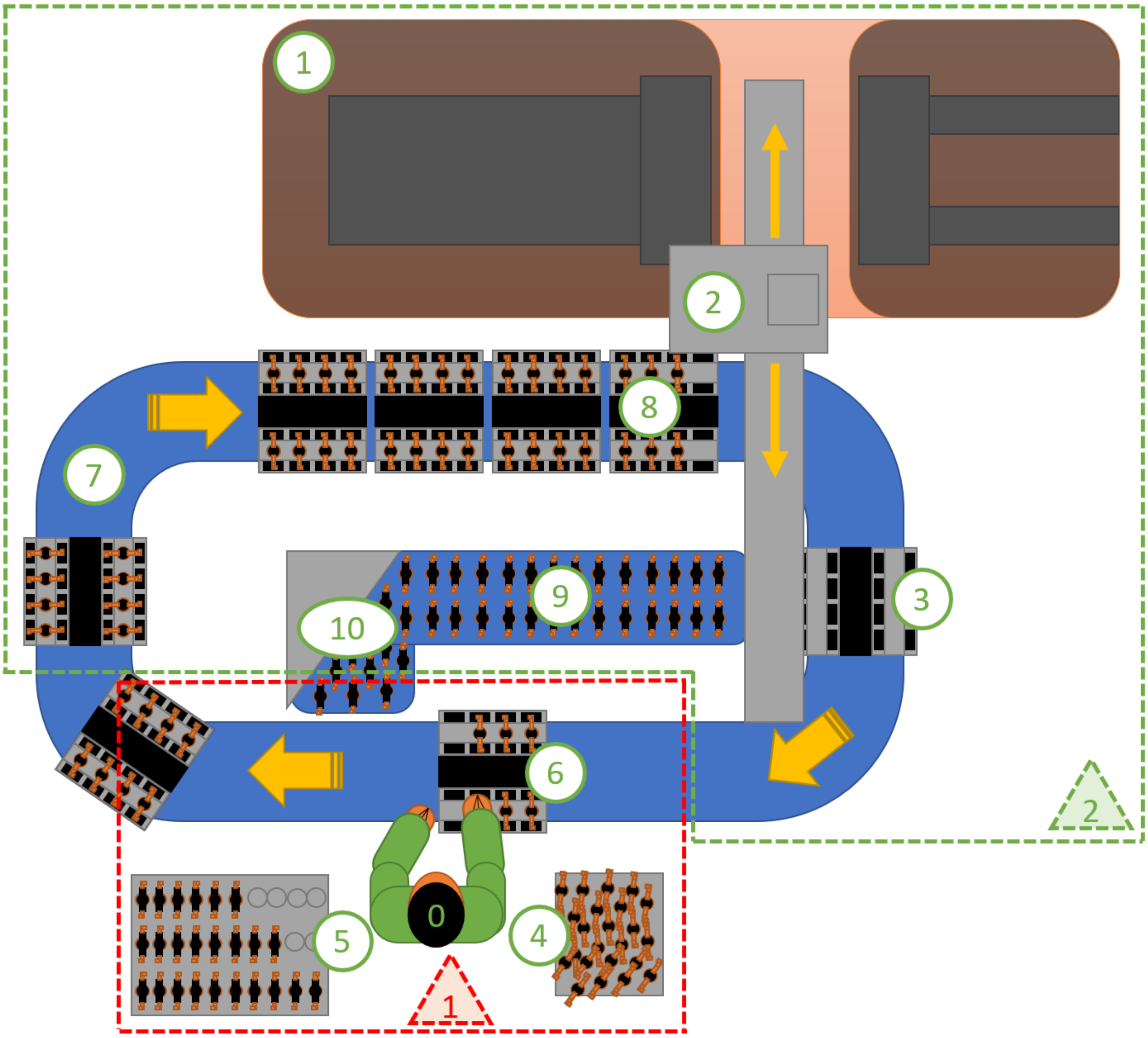


Figure 22: Production cell layout and functions

Once the pallet is in the feed position for the feed robot (2) it is automatically locked in position until it is empty. The injection moulding machine has two cavities, so the robot takes two parts at a time from the pallet.

Gripper of the feed robot (2) is designed in such a manner, that it can hold two finished products and two copper inserts at a time. When it picks up the copper inserts it moves to the IMM (1), waits for the tool die to open, unloads the finished products and loads the copper inserts. Then it moves to the cooling conveyor belt (9) and unloads the finished product from the gripper. The cycle time for producing two parts is 58 s.

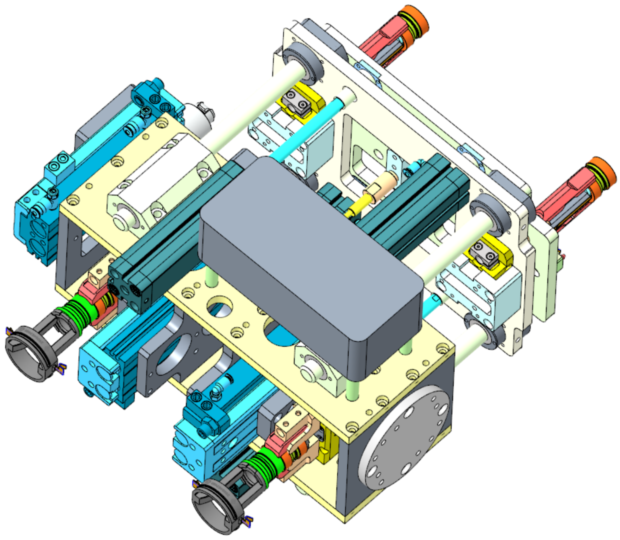


Figure 23: Feed robot gripper tool holding finished products

All the operations on the production line are buffered which means the worker can fill multiple pallets and clear out the finished product in a relatively short time. A much more detailed timing of the process is seen from the MTM diagram in the following chapter.

The production is run 24/7 in three shifts. The capacity of the production line is 800.000 finished products per year at an estimated OEE of 80%. Any implementation and/or modification of the processes must be 100% reliable, so it does not interfere with projected production capacity. For this reason, testing in a simulation environment of the actual part of the production process that is proposed for integration of a collaborative work environment, must be implemented.

3.1.3 Product description

As previously described in chapter 3.1.1 the process is considered hard to automate. This is because the connection rods of the copper inserts are highly flexible. Entire assembly of this semi-product is composed from different materials, then injection molded, and spot welded together. Orientation of the part in the pallet fixtures is important and is distinguished by which sliding ring they connect to (length of connection rods).

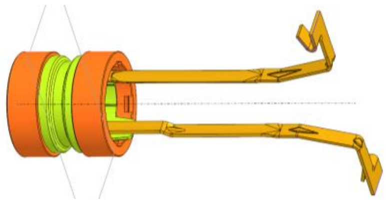


Figure 24: Copper sliding inserts

Copper inserts are supplied on trays and are tightly packed as seen on Figure 20. They tend to get tangled with each other, therefore cannot be simply removed from the tray without movement in multiple degrees of freedom.

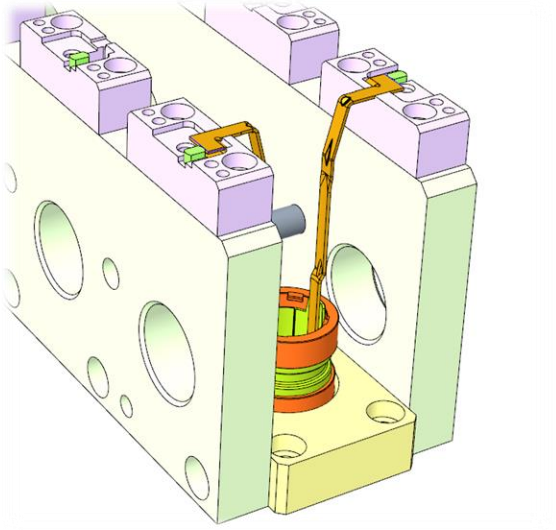


Figure 25: Copper sliding ring inserted into the pallet fixture

Once removed from the tray they need to be mounted into the part fixtures on the pallets. On Figure 25 the representation of how precise the part must be inserted, due to the limitations of the feed robot gripper and the need for precise positioning in the injection molding machine. We estimate that the needed tolerance for positioning the part in the fixture is +/- 0,10 mm but will need to be experimentally proven based on the chosen approach. Part fixtures can also be modified to a certain extent to help the collaborative process of inserting the slide rings into the fixture.

3.1.4 Proposed challenge

The purpose of the challenge is to automate a part of the production line that was considered too hard for implementation with current industrial technologies. With regard to description of the product the challenge can be further divided into three smaller challenges:

1. Picking the part from the tray
2. Placing the part into fixtures
3. Picking up the finished part and placing them into the box

The last (third) challenge is not mandatory for implementation but would improve the automation efficiency. Every aspect of this challenge should be implemented as proposed in chapter *3.1.1 Use case general description and introduction* .

3.1.5 MTM Task analysis for current state of production

The nature of the production line with large buffers has already been optimized for minimal worker interaction within the production process, which is seen in the diagram. The worker serves several production lines and his time is effectively used.

Shown on the operators MTM diagram is the worker filling only one pallet. Depending on the number of production cycles past the last worker interaction with the production line this operation can be multiplied by 7 (only one pallet left at the feed robot position) because the line is buffered. In best case scenario, the production line can be unattended for approximately 27 minutes. In reality this time is around 15 minutes.

Kolektor Challenge: Performing Car Starter Assembly
MTM Task Analysis - Current situation

Index	Type	VAA	Production Line Cycle - Injection Moulding Machine	D (m)	from (s)	to (s)	D (s)
Op-0		-	START		-	0	-
Op-1	G	TR	Injection moulding process	0	0	44,98	44,98
Op-2	A	CO	Open the tool	0	44,98	48,23	3,25
Op-3	C	-	*[Tool opened command]*	0	48,23	48,33	0,1
Op-4	W	PA	Wait for unloading of finished products	0	48,33	51,2	2,87
Op-5	W	PA	Wait for loading of copper inserts	0	51,2	54,68	3,48
Op-6	A	CO	Close the tool	0	54,68	57,93	3,25
Op-7	C	-	*[Tool closed command]*	0	57,93	58,03	0,1
Op-X		-	END		58,03	58,03	58,03

Index	Type	VAA	Production Line Cycle - Feed Robot	D (m)	from (s)	to (s)	D (s)
Op-0		-	START		-	0	-
Op-1	A	TR	Move into position above the cooling conveyour belt	0	0	3,13	3,13
Op-2	A	CO	Release the finished product onto the conveyour belt	0	3,13	3,71	0,58
Op-3	A	TR	Move to wait position	0	3,71	6,22	2,51
Op-4	C	-	*[Feed robot in position command]*	0	6,22	6,32	0,1
Op-5	W	PA	Wait for next cycle to start	0	6,32	7,22	0,9
Op-6	A	TR	Move into position for picking the copper inserts from the pallet	0	7,22	10,39	3,17
Op-7	A	CO	Grasp the semi products	0	10,39	11,17	0,78
Op-8	A	TR	Move into wait position next to IMM	0	11,17	13,72	2,55
Op-9	C	-	*[Feed robot in position command]*	0	13,72	13,82	0,1
Op-10	W	PA	Wait for IMM to finish	0	13,82	48,33	34,51
Op-11	A	TR	Move into position for unloading of IMM	0	48,33	52,13	3,8
Op-12	A	CO	Grasp the finished parts	0	52,13	53,03	0,9
Op-13	A	TR	Move into position for loading the copper inserts	0	53,03	54,15	1,12
Op-14	A	CO	Release the copper inserts inside the tool and move to exit position	0	54,15	55,25	1,1
Op-15	A	TR	Move into position next to IMM	0	55,25	56,98	1,73
Op-16	C	-	*[Feed robot clear command]*	0	56,98	57,08	0,1
Op-17	W	PA	Wait for cycle end	0	57,08	58,03	0,95
Op-X		-	END		58,03	58,03	58,03

Index	Type	VAA	Current Operator's Cycle	D (m)	from (s)	to (s)	D (s)
Op-0		-	START		-	0	-
Op-1	H	TR	*Positioning the semi-product tray [ONCE PER TRAY]*	1,4	0	4,23	4,23
Op-2	H	QU	Picking up the semi product - copper sliding ring (2 pieces)	0	4,23	6,56	2,33
Op-3	M	TR	Moving to the pallet	0,3	6,56	7,02	0,46
Op-4	H	QU	Placing the semi product - copper sliding ring into the pallet fixture 1-2	0	7,02	10,26	3,24
Op-5	M	TR	Moving to the tray	0,3	10,26	10,72	0,46
Op-6	H	QU	Picking up the semi product - copper sliding ring (2 pieces)	0	10,72	13,05	2,33
Op-7	M	TR	Moving to the pallet	0,3	13,05	13,51	0,46
Op-8	H	QU	Placing the semi product - copper sliding ring into the pallet fixture 3-4	0	13,51	16,75	3,24
Op-9	M	TR	Moving to the tray	0,3	16,75	17,21	0,46
Op-10	H	QU	Picking up the semi product - copper sliding ring (2 pieces)	0	17,21	19,54	2,33
Op-11	M	TR	Moving to the pallet	0,3	19,54	20	0,46
Op-12	H	QU	Placing the semi product - copper sliding ring into the pallet fixture 5-6	0	20	23,24	3,24
Op-13	M	TR	Moving to the tray	0,3	23,24	23,7	0,46
Op-14	H	QU	Picking up the semi product - copper sliding ring (2 pieces)	0	23,7	26,03	2,33
Op-15	M	TR	Moving to the pallet	0,3	26,03	26,49	0,46
Op-16	H	QU	Placing the semi product - copper sliding ring into the pallet fixture 7-8	0	26,49	29,73	3,24
Op-17	H	QU	Checking and tapping the parts in fixtures	0	29,73	31,23	1,5
Op-18	C	CO	Press the button to trigger release of the pallet	0	31,23	31,59	0,36
Op-X		-	END		31,59	31,59	31,59

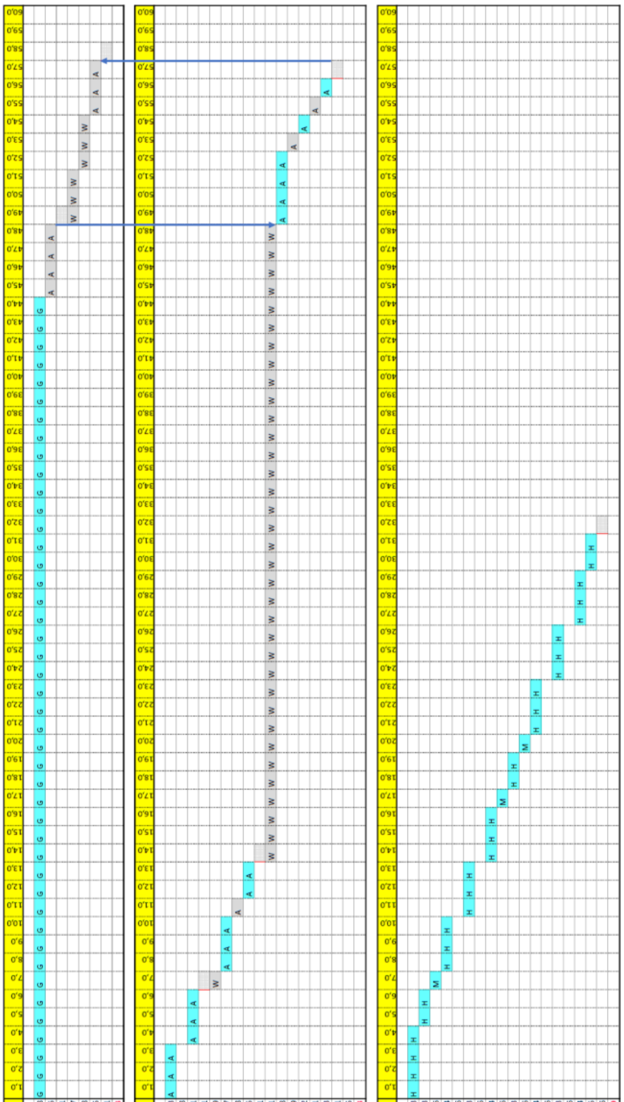


Figure 26: MTM Task analysis of the current process

3.2 CHALLENGE 2: WINDSHIELD VISUAL QUALITY CHECK AND PREASSEMBLY

In current general assembly production lines different use cases require phases of visual inspections and preassembly. While for most of the cases the handled parts are small or relatively small, that means that the operation is easy to be performed manually, in some cases the operation requires the handling of cumbersome or heavy parts to be performed with the aid of manual supports (also known as *partners*: zero weight support manipulators). In these case the operation becomes difficult and requires awkward positions to be performed or eventually the presence of additional fixed supports like table, fixtures and so on.

The CRF use case in the CoLLaboratE project is a use case in which both assembly operations and visual inspections are important on a part which is heavy, cumbersome and eventually fragile. The reference part is the windshield which, according to the reference plant has additional manual operations to be performed by the operator.

The wind shield, especially in high level "premium" vehicles is normally equipped with a plethora of sensors and devices besides of the rearview mirror; its weight is ~10 kg and thus it requires a support for the manipulation and the operator is asked for a visual inspection of defects; the Takt time for Low JPH lines is normally set at a higher level (e.g. 5-6 minutes) and thus many manual operations are left to the line operator.

In shorter Takt time the windshield is normally preassembled at the tier 1 supplier site if compatible with the logistics issues related to the transport of a preassembled part which has a bigger footprint and requires less parts per container to be delivered.

The Challenge 2 of the CoLLaboratE project is based on the windshield assembly process for low JPH process (9-10 JPH). The Use case doesn't aim at the effective modification of an existing line, but it is focused on the realization of a new workcell in which:

1. a front windshield is picked up and manipulated;
2. a visual check of the state of the product is performed to check cleanness, existence of cracks and so on
3. a series of manual assembly phases is performed on top of the windshield in a collaborative way
4. the robot completes the assembly of the windshield on the chassis (gluing if necessary, positioning).

The use case has no real reference to perform experimental tests of the "As Is" situation. The layout will be based on a current one to reproduce a realistic situation, but it will be intended as a green field planning of the operation. Furthermore, in the existing workplace, the operator performs multiple operations which are not connected to phases that the Challenge 2 wants to investigate. The final work-application will thus be reproducing a part of the whole operation as it can be described in Macrocycle of the Mirafiori plant. The attention will thus be focused only to the phases of windshield pick-up, visual check and manual assembly.

In the following paragraphs a description of the reference phases and the "TO BE" work application will be done.

3.2.1 Reference Use-case

The use-case is based on a mixed workstation for the assembly of windshield in a low JPH line. The use case will only be based on the windshield phases though, usually, the same workstation can be used to assemble rear windows too.

The assembly of the windshield on the chassis is usually automatic due to the strong requirements in the positioning (it affects both quality and safety) and the weight of the windshield, thus a robot is always used for the final stages of the assembly.

Since, in the reference workstation, the operator needs accessibility to the inner side of the windshield, the windshield is positioned on a rotating table so that the operator accesses one side and the robot can access the other side after a rotation. Due to the automation present in the workstation, a Safety zone is introduced and monitored with laser scanners so that the operator cannot be nearby the windshield during the rotation phases and the movements of the robot. In order to further limit the accessibility to the dangerous zone, safety fences are positioned to create a corridor which is easily monitored for safety accesses. A safety visual advice is placed on the ground at the limit of the accessible zone (see Figure 27)

With such layout the racks containing the windshield and all the logistics containers and gravity shelves are out of the safety delimited zone. A manipulator (mounted on an overhead rail) depicts the zero gravity material handling system which aids the operator to transfer the windshield from the rack to the rotating table system. These rails ensure the reachability from the source (rack) to the assembly station.

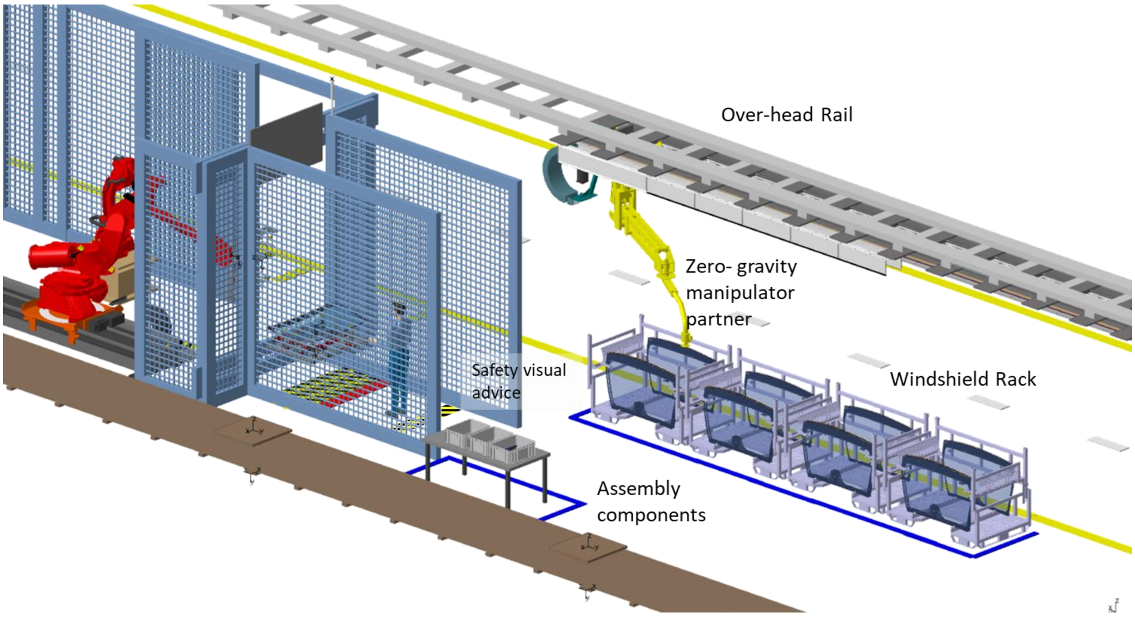


Figure 27: tools and logistics set up in the reference layout

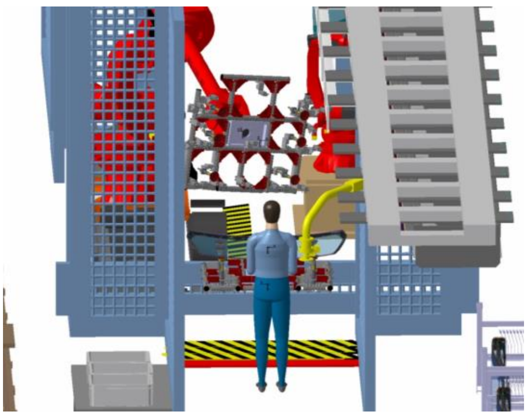


Figure 28: Human operator inside the assembly station.

An HMI monitor updates the operator with the current variant of the product to be assembled. The operator chooses appropriately the components to be assembled.

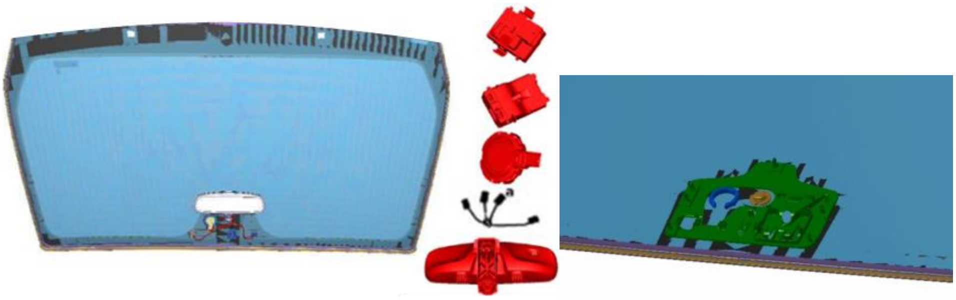
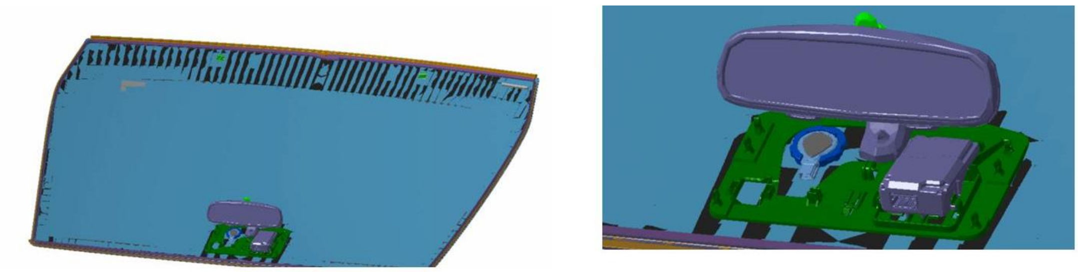


Figure 29: Windshield before assembly and components to be assembled

The rotating table acts as an interface between the human workplace and the robot workstation. The current layout is clearly depicting a traditional layout where humans and robots work in complete isolation, this leads to a very long layout consuming more factory space and also more energy expenditure for the operator to move from one point to another.



(a) Windshield after assembly (Humidity sensor, rain sensor and Rear View Mirror)

(a) Closer view

Figure 30: Windshield after assembly

As from Figure 29 there are 4 sensors and parts to be assembled; after the assembly a cable harness has to be placed. For quality reasons the operator has to clean the windshield before every optical sensor assembly and has to pick up the sensors in a sequence. The coexistence of the safety zone and the quality requirements creates a Spaghetti chart which is extremely long (Figure 31).

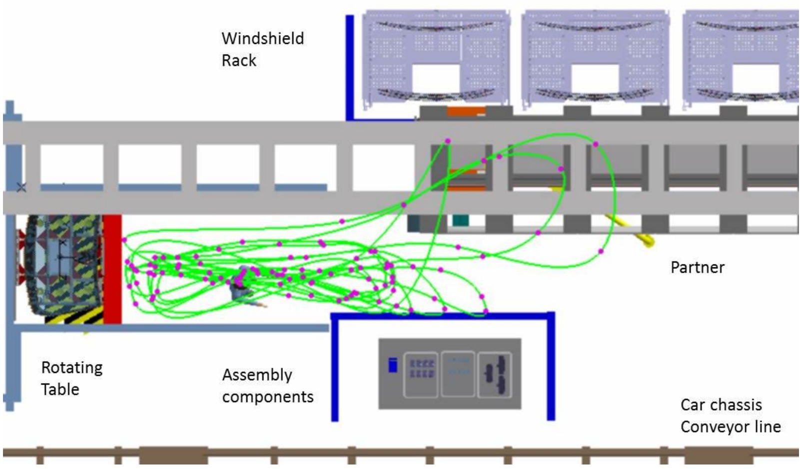


Figure 31: operator's Spaghetti chart

The existing layout does not introduce string ergonomics issues besides of the long spaghetti chart, nevertheless few operations such as the visual check of the windshields and the manual assembly processes performed by the operators are affected by anthropometrics limitations. The rotating table is at a fixed height and this limits the use of the workstation only to a set of suitable operators in order to achieve the full golden zone. Furthermore, the visual check operations are best performed on top of the manipulator which is not ideal for fine manipulation purposes. At last the pushing/pulling actions performed on the manipulator can affect the overall operator's fatigue.

3.2.1.1 Collaborative Workcell

The collaborative layout proposed is modeled in such a way that it encapsulates all the elements of the old layout without compromising on the number of chassis that need to be assembled. The design pertaining to the side of the car chassis conveyor line is not altered.

The workcell is modified to allow the operator perform all the needed operations with an optimized spaghetti chart and logistics positioning; furthermore, the robot used will be such to allow both the manual assembly on top of the windshield and the automatic assembly on the chassis, optimizing thus the overall workstation.

The robot on the rail is similar to the previous layout, since the current objective is to assemble both the front and rear windshield of the car. The robot on the rail would provide enormous flexibility to achieve this objective. We chose NH130, a COMAU 6 DOF serial manipulator to analyze this workcell concept. The robot decision was based on the speculated payload and the amount of human torque that would be exerted by the human operator during operation.

The rail and the gluing devices in the workstation are not accessible to the operator. The operator is only allowed to stand in front of the windshield ant to safely manipulate it from the gripper in an advanced Hand Guiding mode which is further integrated by safety modes and AI provided by the CoLLaboratE project.

The simplified approach is summarized as follows:

Table 6: CoLLaboratE Challenge 2 main expected phases

<table>
<tr><th></th><th>ROBOT</th><th>OPERATOR</th></tr>
<tr><td>1</td><td>Picks up one windshield and goes to an interactive position for the visual check</td><td>Other operations on the workcell</td></tr>
<tr><td>2</td><td>Small movements, driven by the operator in HG or automatic after visual learning by the robot (CoLLaboratE mode)</td><td>Performs the visual check</td></tr>
<tr><td>3</td><td>Goes to the assembly position (defined by anthropometric module in the CoLLaboratE mode)</td><td>Goes to logistics containers</td></tr>
<tr><td>4</td><td rowspan="3">Stationary position or minimal adjustments offering counterforce to assembly operations in golden zone</td><td>Picks up the first towel and sensor</td></tr>
<tr><td>5</td><td>Performs the assembly</td></tr>
<tr><td></td><td>Goes to logistics containers</td></tr>
<tr><td>6</td><td colspan="2">Cyclic repetition (to completed assembly number 4 to 6)</td></tr>
<tr><td>7</td><td>Stationary position or minimal adjustments offering counterforce to assembly operations in golden zone</td><td>Releases the robot and exits the interactive zone</td></tr>
<tr><td>8</td><td>Assembles the windshield to the chassis</td><td>Performs other operations on the workcell</td></tr>
</table>

During all above operations the operator is capable to interact with the robot only from the front part of the windshield or using the sensitive gripper acting as a HG input device (though distributed spatially). Figure 32 and Figure 33 give a representation of the aimed layout with safety zones.

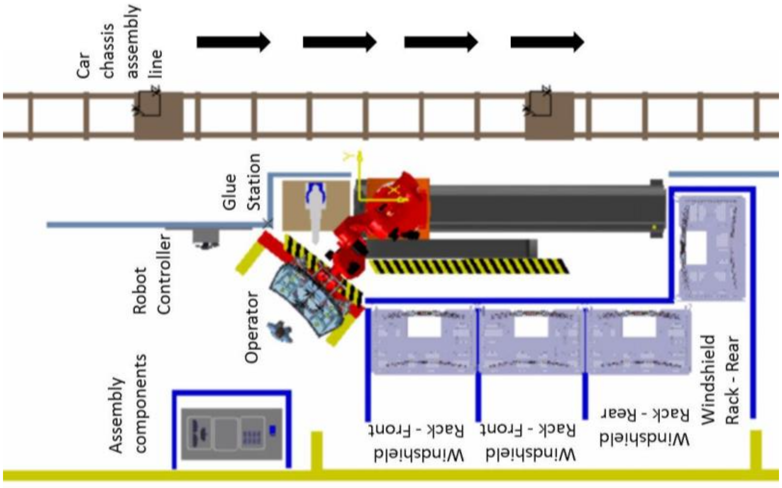


Figure 32: Challenge 2: Collaborative Layout

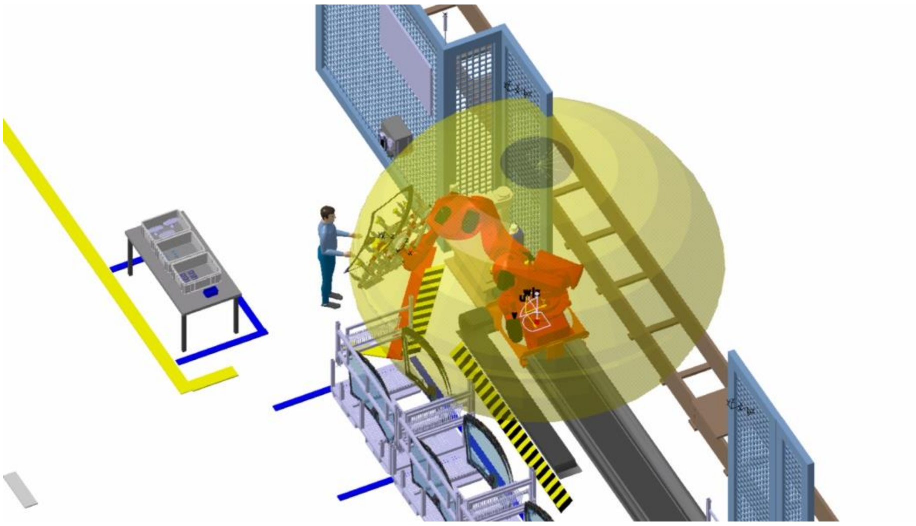


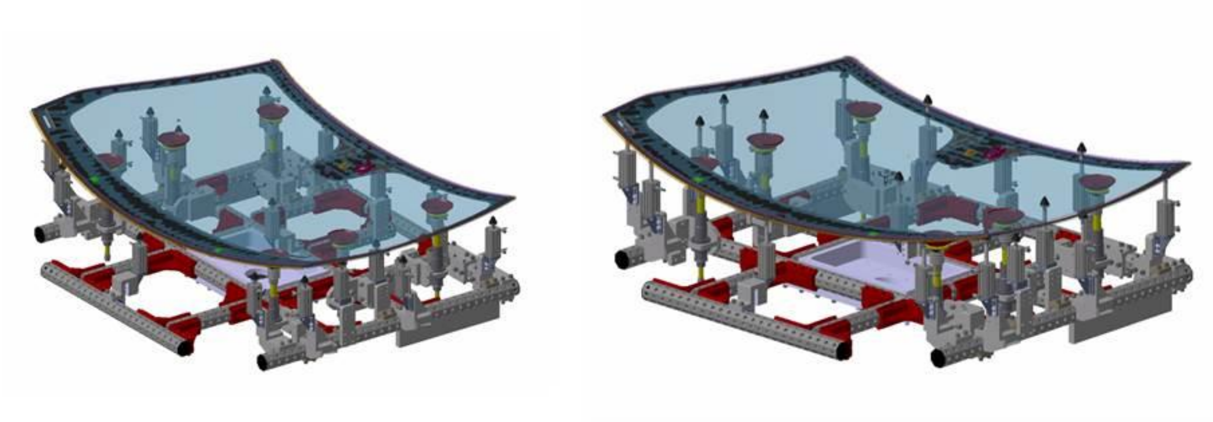
Figure 33: Challenge 2: Collaborative Layout

3.2.1.2 Payload Analysis

Estimating the payload of the robot is essential for the selection of the robot. In this particular use-case, of windshield assembly, the main components to be analyzed for estimating the payload are (i) Gripper (ii) Workpiece (windshield).

The considerations made in this deliverable are based on an initial design of the gripper, where existing gripper in process is modified to accommodate the robot flange. In order to define this draft level of gripper a full evaluation of the torques that the operator could perform on the robot's flange have been evaluated.

Figure 34 represents the initial design. Vacuum cups are placed along the gripper to pick up the windshield from the rack and fixture them appropriately while the operator performs the assembly operation on the windshield. Pneumatic cylinders are provided all over the workpiece to aid in the final operation of mounting the windshield on the chassis of the car. The pneumatic cylinders provide the necessary uniform force to have a good assembly. For the initial design, the material for the frame and clamps are assumed to be of Aluminum to achieve a lightweight design.



(a) Gripper Grasping (Piston Retracted) (b) Gripper Mounting windshield on chassis (Piston Extended)

Figure 34: Draft gripper definition for robot dimensioning phases

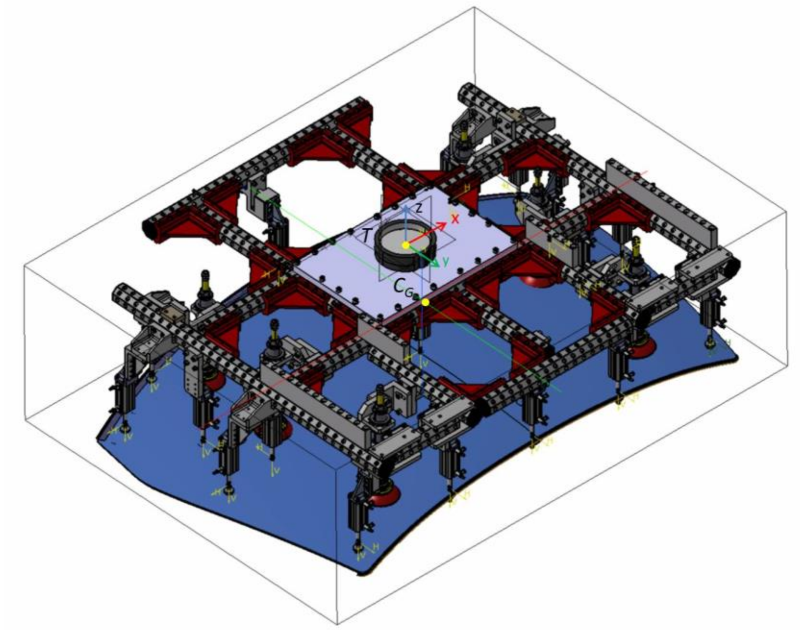


Figure 35: Representation of Gripper Centre of Gravity.

Based on the above draft design, an evaluation of the payload parameters have been performed. To complement the robot skin, in this use-case, a load cell would be mounted on the collaborative robot. The load cell can provide detailed information on all forces and torques in 6D the operator applies on the gripper. Hence, the collaborative robot can react accurately based on the load cell readings. While testing the suitability of the COMAU NJ 130-2.6, it is necessary to choose the load cell model. Based on the operating condition, we estimate the load cell to be ATI Theta with a weight of 4.99 kg. Hence, we take into account the load cell weight also for the payload analysis.

Few COMAU variants were tested for operating feasibility with the above mentioned parameters. As from the results for the payload analysis with COMAU SMART-5 Robot NJ 130 - 2.6, we can demonstrate that the robot is suitable to handle the payload even with its rated maximum velocity.

Various layouts had been studied with different configuration for picking from the rack, but accommodating two front windshield and rear windshield rack in the same workcell exposed to be a difficulty. A dedicated rack was designed to enable grasping from the outer side of the windshield. This strategy ensures assembly can be performed immediately after the gripper mounts the windshield. In the current design, an operator needs to disengage the clamps on the rack once before the assembly starts (once every 12 cycles).

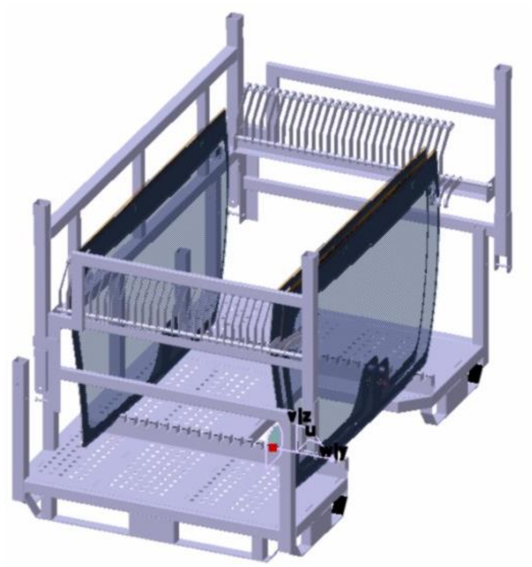


Figure 36: CAD Model of Rack with windshields

Assembly components are placed as shown inside the blue border tape. By observation, we can understand that the distance traveled by the human operator is minimized. The operator manipulates the robot in a diagonal fashion. This architecture was chosen to ensure maximum manipulability within the collaborative region. An HMI screen is provided on the adjacent enclosure to update the current assembly variant. Also, a robot controller is provided as a backup and to manipulate the robot when collaboration is not happening.

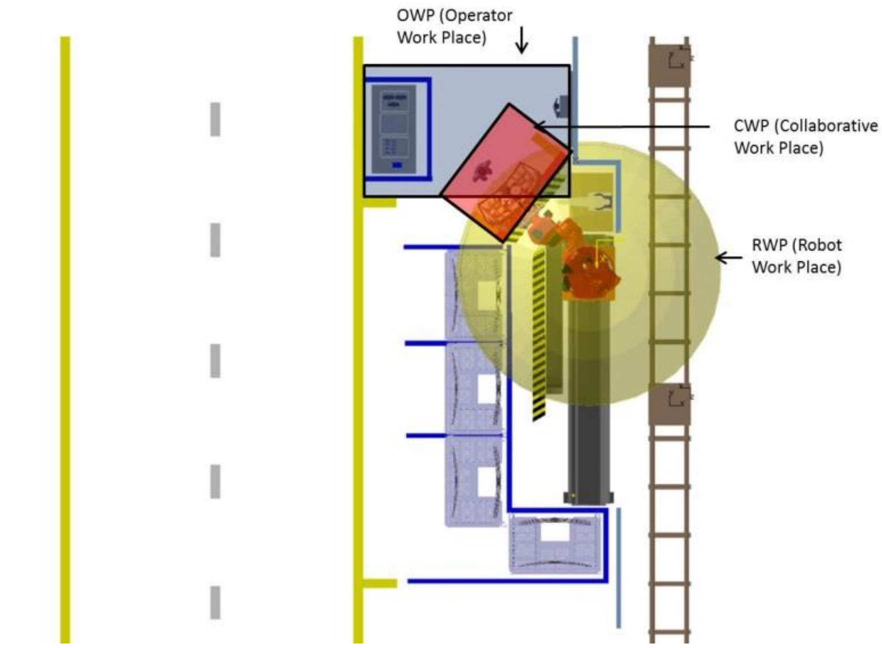


Figure 37: Collaborative Workspace detailed for the Windshield use case, Blue (OWP), Yellow (RWP), Red (CWP)

In the current workcell, there is no physical barrier separating the operator from the robot, a logical barrier is denoted using a red tape. Cameras would be placed around the workcell once the architecture is finalized to monitor and take proactive and preemptive safety steps to ensure there is no harm to the human.

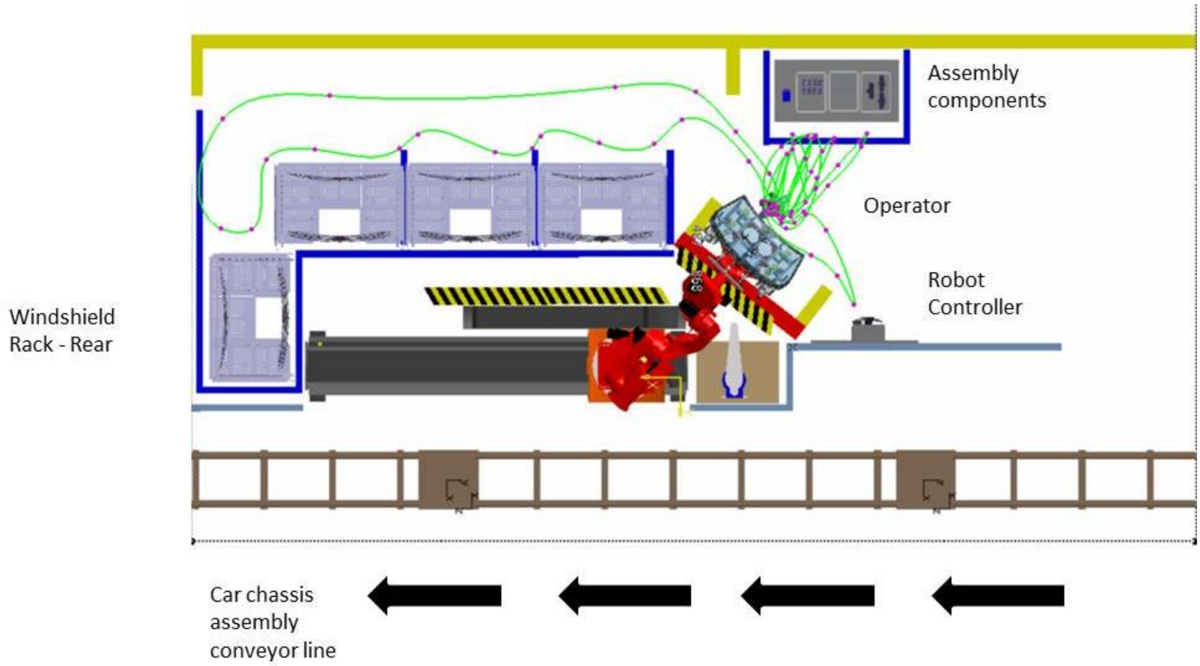
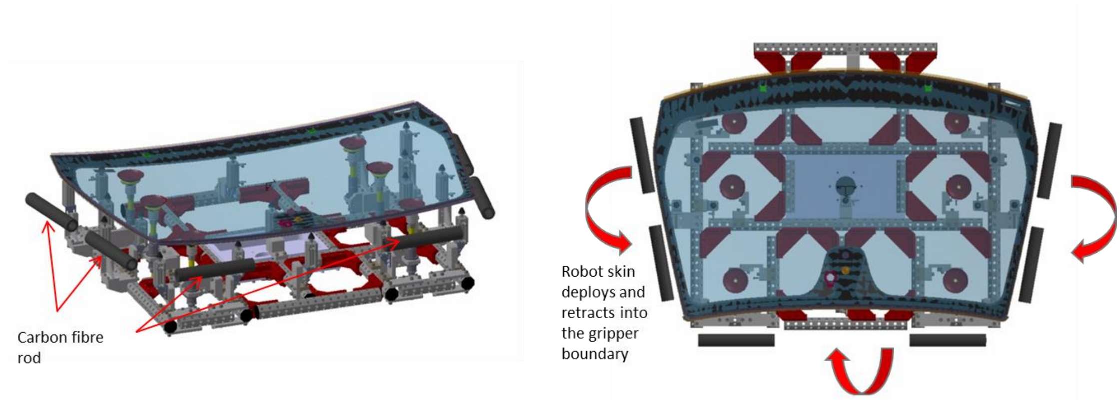


Figure 38: Spaghetti chart of New Collaborative Workcell

The total distance required to cover by the operator (spaghetti chart) was reduced by almost 50 % using the collaborative workcell. Further reduction in human energy can be obtained by automating the windshield rack retainer mechanism. The layout shown is a preliminary one, where further recursions would be made according to the practical feasibility while manufacturing and implementing in a real case scenario.

As for the Ergonomics considerations in the workcell, the use of the robot allows the implementation of a workcell which is constantly in Golden zone for all the work phases. To show this approach an initial concept layout of the gripper have been made with a detail of the manipulation zones onboard of the gripper (see Figure 39). On the manipulation zones (which could be retractable to ensure both the pick-up phases from the container) it is planned to install a sensitive skin which, properly interpreted, will furnish information on forces, activities and willingness of the actions performed by the operators.

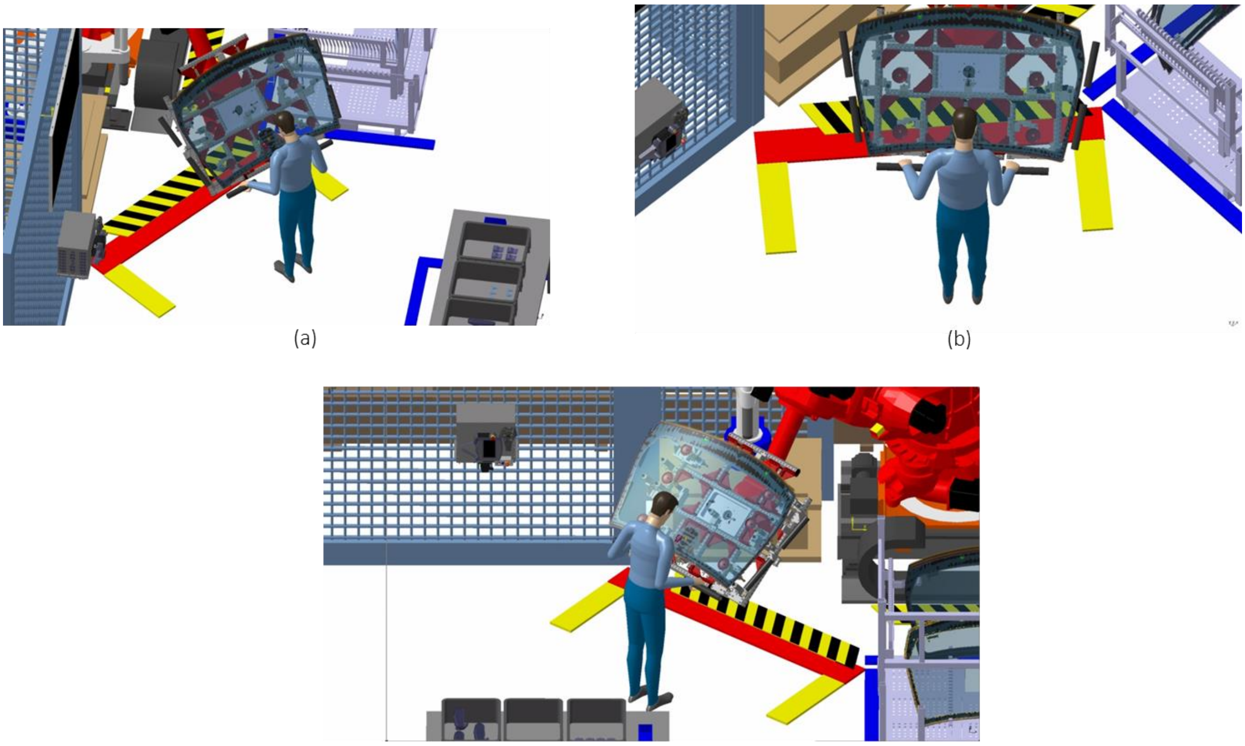


(a) Carbon fibre rod depiction to locate the necessary robot skin

(b) Carbon fibre rod depiction to locate the necessary robot skin

Figure 39: Conceptual Windshield Gripper to place Robot Skin for Human Interaction.

Based on this concept of gripper an initial set of layout verification can be done showing the achievement of the golden zone for all the main work phases in the application (see Figure 40).



(a) (b) (c)

Figure 40: Concept visualization of operator manipulating the windshield assembly

A full Task analysis have been performed with the detailed description of the robotic phases and interfaces, but it won't be represented in this deliverable for confidentiality limitations. All the operations performed in the traditional workstation are here performed with an improved spaghetti chart, a more controlled ergonomics and without compromising the operator's safety. The safety zone defined in the short description above is the minimal one, but the realization of a dynamic safety zone can modify the safety zone dynamically. Active, dynamic safety signs can be projected on the pavement to ensure a continuous update of the safety zones for the operator. The workstations' cost will be reduced thanks to the elimination of the rotating table and the manipulator; in addition the workstation footprint will thus be limited. Last but not least the use of the same robot for the handling and assembly phases reduces the execution time.

3.3 CHALLENGE 3: PERFORMING LCD TV ASSEMBLY

Third challenge within the CoLLaboratE is LCD TV electronic card assembly and screwing operation. The operation consists of two parts, which are done manually by two different operators currently. First part of the assembly covers the picking of the electronic cards called power supply unit (PSU) and main board (chassis) from their boxes and placement of them on the TV; while the second part is the screwing of these cards on the TV by 7-8 screws.

3.3.1 Use case general description and introduction

Electronic cards are the main components of the TV, consisting of all physical connection ports (USB, HDMI, VGA, AUX…), processors, power electronics layer and firmware. Due to their high costs and fragile design electronic cards require special attention during the assembly stage. There are two different electronic cards within each TV, the power supply unit (PSU) and the main board (chassis). PSU is responsible for power electronics operations, such as AC to DC conversion and voltage regulation; chassis on the other hand is the core element that contains the processor and runs the firmware and software of the TV. The examples of PSU and chassis as well as their locations on a TV are given in Figure 41 below.

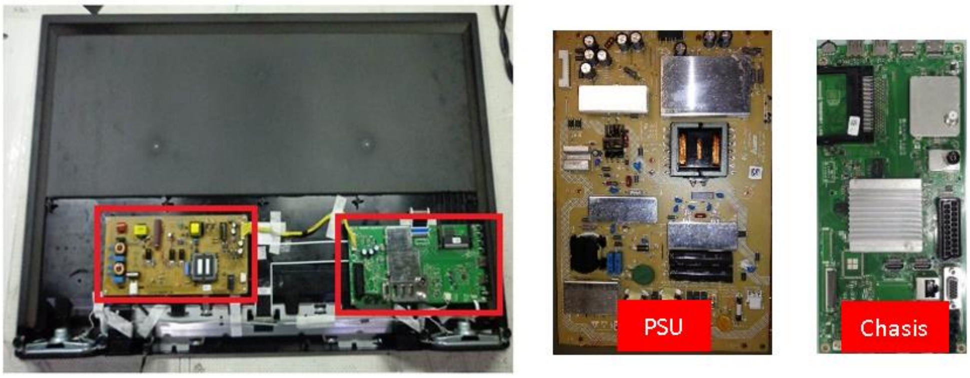


Figure 41. PSU and chassis

Both PSU and chassis are stored and transferred in special Electro-Static Discharge (ESD) protected half euro box sized containers within the factory. (See Figure 42) Electro Static Discharge (ESD) is the most common reasons for electronic card failure, which happens during the handling of the cards by operators.

Figure 42. ESD Box for electronic cards

PSU and chassis are assembled in the same station on the production line. The station has two work cells, one on the right and one on the left side of the assembly line. The assembly line runs continuously, making any kind of automation harder. The overall layout and picture of the station is given in Figure 43 below.

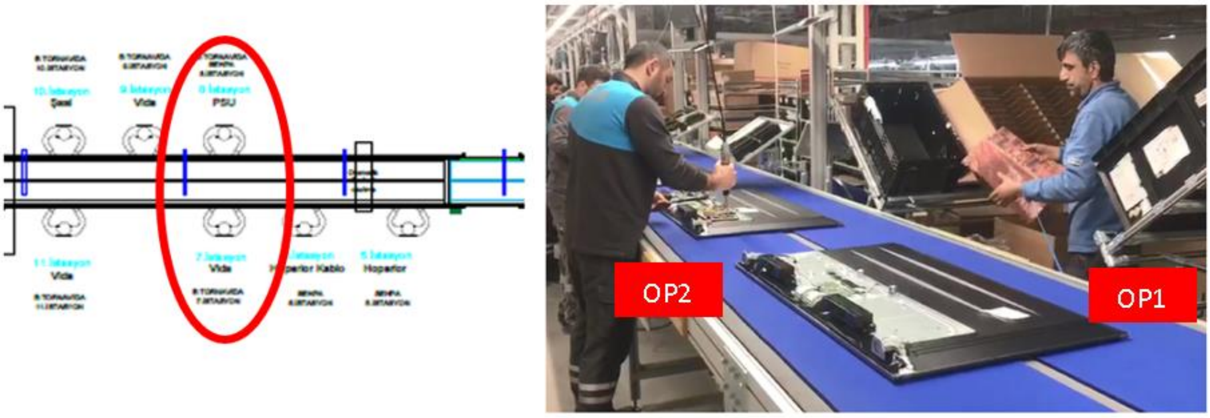


Figure 43. Layout of the card assembly station

Electronic card assembly operation is done in two steps, first step is the placement of the cards on the TV and the second step is the screwing them on the TV. Both steps are repeated in the same order for each of the PSU and chassis. Operator 1 (OP1), the one on the right side of the line, is responsible for the electronic card placement; while Operator 2 (OP2) is responsible for the screwing operation.

Operation steps and the cycle time analysis of the operators are given in Figure 44 below.

Index	Current Operator's Cycle	from (s)	to (s)	D (s)
Op-0	START	0	-	
Op1-1	Pick PSU from the box	0	4,8	4,8
Op1-2	Place it on the TV	4,8	7,6	2,8
Op1-3	Pick Chasis from the box	7,6	12	4,4
Op1-4	Place it on the TV	12	15,2	3,2
Op2-1	Pick screws from the box	0	1,8	1,8
Op2-2	Screwing of PSU	0	10,4	9,4
Op2-3	Screwing of Chasis	10,4	17,4	7
	END			

Figure 44. Operation steps and time analysis

The electronic card assembly operation is one example of many similar operations in TV production process. There are other operations such as taping, cabling and configuration that are done in a similar way to the electronic card assembly. All these operations require two operators working on the same workpiece at the same time. The solution to be developed within the CoLLaboratE project will be disseminated to these operations as well. The human-robot collaboration methodology /blueprint will be applied to the other production plants of Arçelik for home appliances production. Starting with the operations that require two operators, CoLLaboratE outputs will be transferred to refrigerator, washing machine, dishwasher, cooker, dryer and electric motor factories of Arçelik worldwide.

3.3.2 CoLLaboratE Solution

The electronic card assembly operation is quite suitable to human-robot collaboration due to its workspace and job-sharing nature. The proposed solution by the CoLLaboratE project will consist of the following steps:

- Replacement of Operator 1 with a collaborative robot (Universal Robots UR5)
- Enhancing the robot safety with specially designed sensors/robot skin
- Integration of vision system to detect electronic cards within the boxes
- ESD protected gripper design for electronic card handling

- Conveyor tracking algorithm for card placement on the TV
- Gesture recognition for seamless communication between the COBOT & operator & AGV
- AGV adaptation for electronic card feeding, from warehouse to the assembly line

Ergonomic risk assessment of the current manual operation will also be analyzed to be able to measure the improvement after CoLLaboratE solution. Improving the overall operator health and safety is another aspect of the project. The layout for the planned solution is given in Figure 45. The REBA ergonomic risk assessment result for the operator 1 is given in Figure 46.

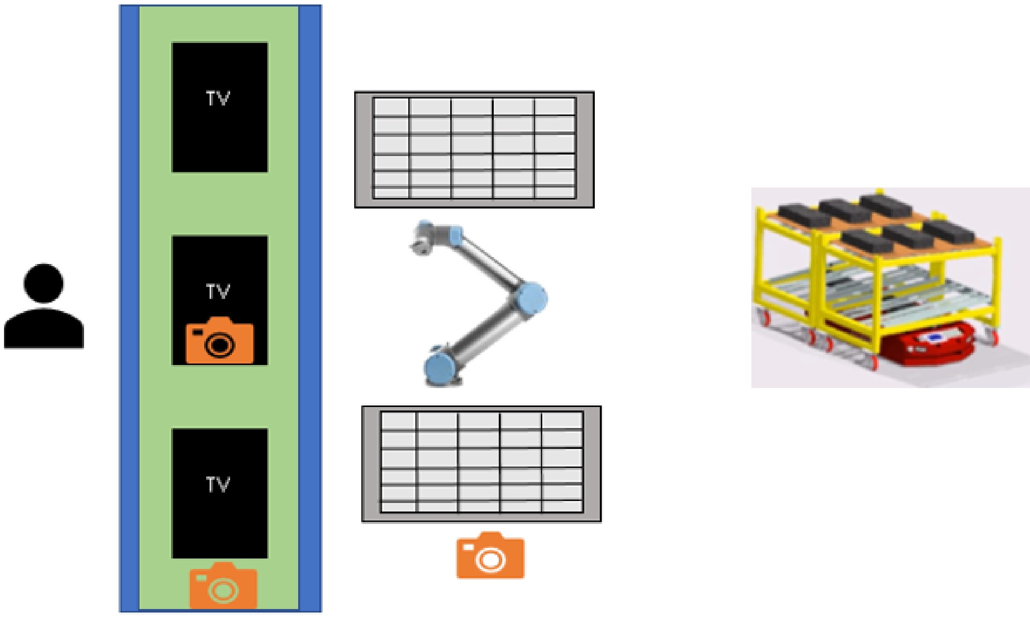


Figure 45. Solution layout

3.3.3 Proposed Challenges

Electronic card assembly operation is chosen within the concept of CoLLaboratE project for several reasons. The technical challenges proposed with this specific use case are as follows:

- Robotic automation on a continuous production line:

Continuous production lines are not as suitable as the stop & go systems regarding to the automation projects. Precise conveyor tracking algorithms are required for the system to be developed. Back-up systems are required in case of any machine/robot failure in order not to stop the entire line. Advanced mechanical design skills are required to physically stabilize moving parts.

	REBA Score	
NOTES:	MM No	
	MM Title	
	Station	PSU&Chasis Placement
	Investigator	Cansu Okur
	Date	22.01.2019

Category	Score
Neck Position	2
Body Position	3
Leg Position	1

Category	Score
Carried weight	0
Grasping position	0
Activity Intensity	1

Upper Arm Position	2
Lower Arm Position	1
Wrist Position	2

Overall Score	7
Medium risk, further investigation, change soon	

Figure 46. REBA score for Operator 1

- Work cell design for human-robot collaboration:

The robot usage in the TV production was limited with the industrial robots so far. Introduction of the collaborative robots and collaborative systems brings new design constraints to the shop floors. The physical interaction between the COBOTs and a human operator depends on the both structural and electrical design of the work cell, which the collaboration takes place between two sides. The work cell designed within the scope of the CoLLaboratE project will be a blueprint for the further collaborative robot projects for Arçelik.

- Workspace and job sharing:

The proposed CoLLaboratE solution to the electronic card assembly operation requires a workspace sharing between the COBOT and the human operator. Both the COBOT and operator works on the same workpiece, TV. The communication between the COBOT and the operator needs to be seamless, any latency in the communication directly effects the entire production line. Hand gestures and body language will be used for this high-level interaction. Special algorithms for the shop floor environment need to be developed. Due to the consecutive nature of the operation, job sharing algorithms are also needed to optimize the process.

3.4 Challenge 4: Collaborative riveting for aircraft parts assembly

Challenge 4, as described in the proposal of the project consisted in "Preparing CNC tools for aircraft parts manufacturing". Immediately after the start of the project, in October 2018, a modification in the consortium's structure occurred. The partner responsible with the implementation of the 4th industrial Use Case (Challenge 4) – Pratt & Whitney Rzeszow Spolk A AKCYJNA (PWR) decided to withdraw from the project. ROMAERO SA (ROMAERO) was identified as an appropriate partner that could replace PWR by bringing to the project similar competences in the field of aerospace industry manufacturing and assembly. Soon after joining the project, ROMAERO presented to the CoLLaboratE consortium a number of potential industrial Use Cases for the demonstration of the modules developed within the project, as a replacement of the activity originally planned for Challenge 4. These potential cases covered three distinct manufacturing fields, namely:

- CNC machining (with three subcases)
- Chemical milling (with two subcases)
- Assembly of aeronautical structures by riveting

Out of the three potential Use Case categories, the assembly of aeronautical structures by riveting was unanimously adopted by the consortium as the most appropriate case for the project's needs. The selection of the Use Case was performed taking into consideration the following aspects:

- The use case needs to rely on the strong human – machine collaboration following the implementation of the robot in the production/assembly sequence
- The industrial activity needs to consist in the manufacturing/assembly of a product with an aeronautical application
- The limitations of the existing collaborative robots need to be taken into account, in terms of dimensions and maximum lifting capability or exerted force.

As a consequence, the activity retained for this industrial Use Case is the assembly of the float of the CL-415 aircraft – see Figure 47. The assembly is performed by riveting. The riveting process involves a truly collaborative sequence between two human operators. Replacing one of the operators with an industrial robot is challenging, but extremely useful for the project's needs.

One float, identical to the ones produced by ROMAERO on a commercial basis will be assembled specifically for the project.

Figure 47: CL-415's float subcomponent - installation and assembly

3.4.1 Task analysis

The component parts of the float are manufactured in house by a series of processes like mechanical stretching, press forming, bending and machining. The components are then transported in the assembly shop.

Step 1:

Mounting of the components on an assembly jig and assembly with a limited number of temporary fasteners – see Figure 48**.** These temporary fasteners, also called Cleco fasteners, are installed in pre-drilled holes to hold the materials in place; those same holes will later be used for the installation of permanent rivets, with the Cleco fasteners being removed prior to permanent rivet installation.

Figure 48: Temporary fasteners

This first step of the process is accomplished on a specially designed metallic assembly jig which holds in place all the major components. The components of the subassembly are progressively added to the float and fixed together with temporary fasteners. One or two technicians perform the following: clamp the new added parts, transfer the pilot holes, and install the temporary fasteners.

Step 2:

Full, permanent riveting of the structure.

This step of the process consists in placing a large number of permanent rivets for connecting all the components. This operation can be further divided into a series of smaller steps:

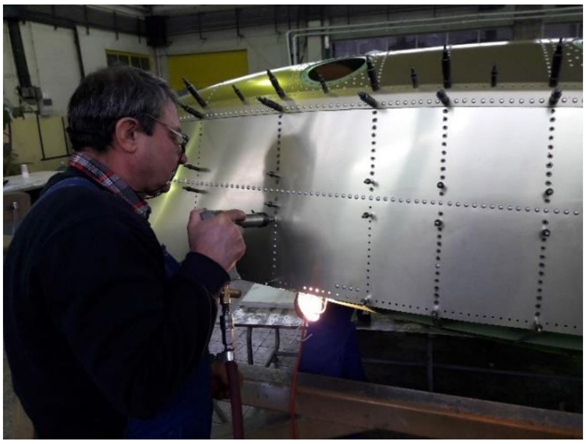


Figure 49: Operator performing riveting on the float

- **Step 2.1:** a series of holes are performed on the to-be-assembled structure. After executing a given number of holes, extra temporary fasteners are added to the structure to increase its stability, to maintain the right position and to ensure that no relative movement occurs between the materials, as this would lead to misalignment of the holes.
- **Step 2.2:** Cleaning the holes – removing the metallic debris resulting in the drilling process
- **Step 2.3:** Placing the sealant in each hole, before inserting the rivet
- **Step 2.4:** Performing the permanent riveting
- **Step 2.5:** Removing the temporary fasteners and replacing them with permanent rivets

During step 2, the position of the float is changed multiple times so that the workers have access to different regions of the float; the float is rotated around its axis so that it facilitates access – see Figure 50.

Step 3:

Verification of the water-proof characteristics.

This final step consists in filling the float with water. If a leakage is observed around one of the rivets, or in any part of the assembly, the problem needs to be addressed, as one of the requirements of the float is to be water proof.

Figure 50: Float installation on its support for riveting

The process to be addressed in this project is the actual riveting – **Step 2.4** mentioned above. Riveting requires a compressive force to be exerted on the rivet, from two sides simultaneously: an active force on the rivet head and a passive, counteracting force, on the rivet pin. The regions where this counteractive force needs to be applied are difficult to reach. As a consequence, the workers that perform this job need to have strong, long arms and be able to work for long periods of time in uncomfortable positions. In addition, they are subjected to vibrations induced by the pneumatic hammer which can be damaging, especially if the exposure times are long.

The riveting process is described in detail hereafter.

Following the addition of the sealant in the holes to be riveted, the actual riveting process begins. This process contains a sequence of operations that facilitate the collaborative work of the two technicians (although there is no visual contact between the two) for the matching of the positions of the riveting hammer and of the handheld bucking bar. This is a type of sensorial communication between the two workers which, most likely, will need to be reproduced by the robot. As the robot will replace only one of the technicians, the behavior of the machine will need to closely follow the human behavior so that the remaining human technician can perform his activity in a condition as similar as possible to the current condition, when no robot is in the loop. The positioning of each worker in the sequence below, relative to the float's wall, is given in Figure 50.

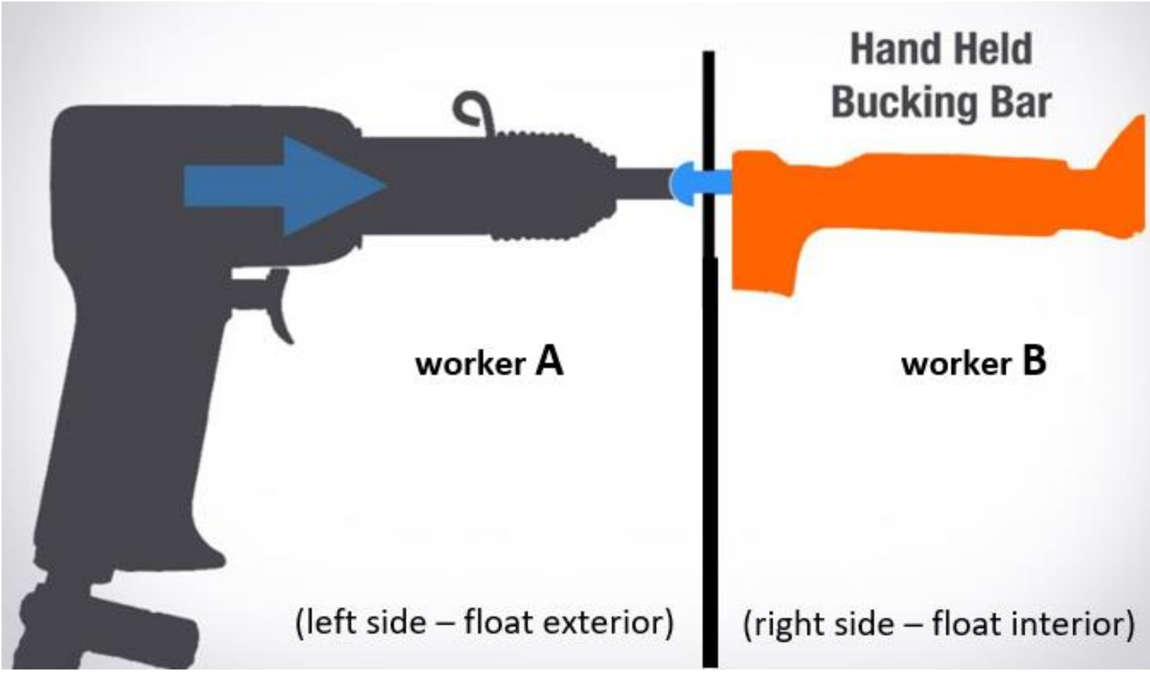


Figure 51: Principle of percussive riveting

Step 2.4.1: Worker A inserts the rivet into the hole and gently presses the rivet until the flat side of the rivet head touches the surface of the metal.

Step 2.4.2: Worker A puts the head of the pneumatic hammer on the rivet's head and gently presses on the hammer, thus exerting a constant, small force on the rivet.

Step 2.4.3: Worker B brings the bucking bar close to the rivet pin, puts the bucking bar head in contact with the rivet pin and exerts a force slightly higher than the force exerted by worker A. This will cause the rivet to move towards worker A (towards the left side in Figure 50).

Step 2.4.4: Worker A senses that the rivet is being pushed towards him and he/she increases the force exerted on the rivet head, until this force becomes higher than the force exerted by worker B. It follows that the rivet starts to move towards worker B (towards the right side in Figure 50), until the flat side of the rivet head gets in contact with the surface of the aircraft part.

Step 2.4.5: At this point, the two tools (pneumatic hammer and bucking bar) are in position. Worker B announces worker A by vocal command when to start the pneumatic hammer: he/she shouts "Go!!".

Step 2.4.6: When worker A hears the "Go!!" signal, he/she turns on the pneumatic hammer. This results in a round of high-frequency mechanical shocks that are transmitted to the rivet and gradually compress the rivet pin and flatten it.

Step 2.4.7: Worker A stops the pneumatic hammer after less than one second, but keeps the hammer in contact with the rivet head.

Step 2.4.8: When worker B hears that worker A has stopped the hammer, he/she removes the bucking bar from the rivet.

Step 2.4.9: After removing the bucking bar from the deformed rivet pin, worker B visually verifies whether the riveting has been correctly performed or not, according to a technological specification imposed by the OEM. If the visual test is passed, he/she announces worker A that the riveting was successful, and they proceed to riveting the next hole.

Step 2.4.10: If the visual test is not passed, worker B announces worker A that an extra hammering session is required.

Step 2.4.11: Worker B puts the bucking bar back on the deformed rivet pin.

Step 2.4.12: Worker B starts exerting a force on the deformed rivet pin (a force similar to the one he/she exerted in steps 2.4.3 to 2.4.7) and immediately after exerting this force he/she announces worker A by vocal command when to start the pneumatic hammer. He/she shouts "Go!!".

Step 2.4.13: When worker A hears the "Go!!" signal, he/she starts the pneumatic hammer. This compresses the rivet pin and flattens it further.

Step 2.4.14: Worker A stops the pneumatic hammer. The hammering time is shorter than the hammering time in Step 2.4.6, less than half the time. After stopping the hammer, he/she removes it from the rivet head.

Step 2.4.15: When worker B hears that worker A has stopped the hammer, he/she removes the bucking bar from the rivet.

Step 2.4.16: After removing the bucking bar from the deformed rivet pin, worker B visually verifies whether the riveting has been correctly performed or not. If the visual test is passed, he/she announces worker A that the riveting has now been successfully performed and they proceed to riveting the next hole. Otherwise, the sequence is repeated from **Step 2.4.10**.

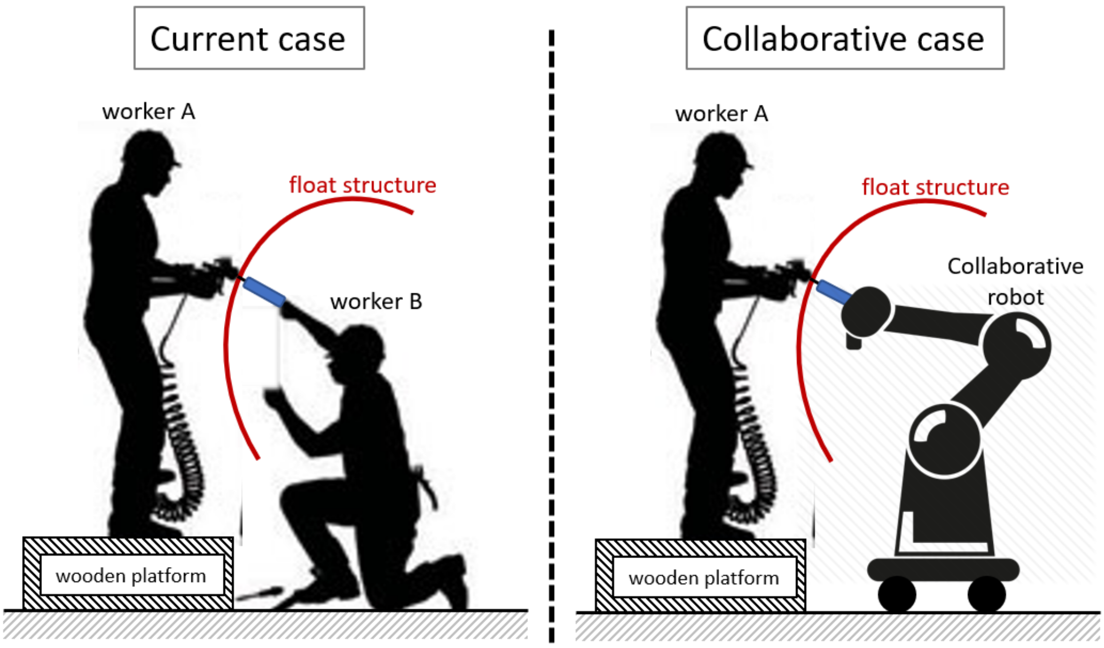


Figure 52: The principle of collaborative riveting

Steps 2.4.10 to 2.4.16 may be repeated several times (normally two times, but 3 or more times is not unusual) if worker B considers that the riveting operation was not successful. A time-dependent description of this sequence, with more details, is given graphically in Figure 53.

The proposed principle of the to-be-developed collaborative riveting is shown in Figure 52: The principle of collaborative riveting. Worker B (the one holding the bucking bar) is to be replaced by a collaborative robot. The introduction of the robot will have no impact (or the impact will be minimal) on the activity of worker A.

The required measures will be taken to ensure that there is a two-way communication between worker A and the robot and that the robot has the required flexibility and mobility to perform the tasks that were initially performed by worker B.

	Index	Type	VAA	Operator's working cycle	D (m)	from (s)	to (s)	D (s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Operator A	op-0			start		-	0.0																	
	op-1	H	CO	*[Take the drilling tool from its support]*	1.5	0.0	5.0	5.0	H	H	H	H	H	H										
	op-2	H	TR	*[Clean the hole of metallic debris]*	0.0	5.0	7.0	2.0							H	H								
	op-3	H	CO	*[Put back the drilling tool on its support]*	1.5	7.0	10.0	3.0									H	H	H					
	op-4	H	CO	*[Take the sealant dispensing tool from its support]*	1.5	10.0	12.0	2.0												H	H			
	op-5	H	TR	*[Dispense the sealant in the hole]*	0.0	12.0	13.0	1.0														H		
	op-6	H	CO	*[Put back the sealant dispensing tool on its support]*	1.5	13.0	15.0	2.0															H	H
	op-7	H	CO	*[Take the pneumatic hammer from its support]*	2.0	15.0	19.0	4.0																
	op-8	H	CO	Take a rivet from the box	1.0	19.0	23.0	4.0																
	op-9	H	CO	Insert the rivet into the hole	0.0	23.0	27.0	4.0																
	op-10	C	-	*[Let Operator B know where the rivet was inserted]*	0.0	27.0	29.0	2.0																
	op-11	H	CO	Put the tip of the pneumatic hammer on the rivet head	0.0	29.0	31.0	2.0																
	op-12	W	PA	Wait	0.0	31.0	42.0	11.0																
	op-13	C	TR	Activate the hammer and perform the riveting	0.0	42.0	42.7	0.7																
	op-14	W	PA	Wait	0.0	42.7	56.0	13.3																
	op-15	C	TR	*[Activate the hammer and perform the riveting (2nd trial)]*	0.0	56.0	56.5	0.5																
	op-16	W	PA	*[Wait]*	0.0	56.5	61.0	4.5																
	op-17	H	CO	Remove the pneumatic hammer tip from the rivet's head	0.0	61.0	63.0	2.0																
Operator B	op-0			start		-	0.0																	
	op-1	W	PA	Wait		0.0	20.0	20.0	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
	op-2	H	CO	*[Position the light source to have visibility on the rivet]*	0.5	20.0	28.0	8.0																
	op-3	H	TR	*[Remove the extra sealant from around the inserted rivet]*	0.0	28.0	34.0	6.0																
	op-4	H	CO	Clean the bucking bar's head of sealant	0.0	34.0	39.0	5.0																
	op-5	H	CO	Put the bucking bar in contact with the rivet pin	0.5	39.0	42.0	3.0																
	op-6	C	-	Instruct Operator A to start the pneumatic hammer	0.0	42.0	42.7	0.7																
	op-7	H	CO	Remove the bucking bar from the rivet pin	0.5	42.7	44.0	1.3																
	op-8	M	QU	Perform visual control of the riveting	0.0	44.0	48.0	4.0																
	op-9	M	QU	*[Touch the upset rivet pin (perform sensorial control)]*	0.5	48.0	52.0	4.0																
	op-10	C	-	*[Inform Operator A that another session is required for the same rivet]*	0.0	52.0	53.0	1.0																
	op-11	H	CO	*[Put the bucking bar back in contact with the rivet pin]*	0.5	53.0	56.0	3.0																
	op-12	C	-	*[Instruct Operator A to start the pneumatic hammer]*	0.0	56.0	56.5	0.5																
	op-13	H	CO	*[Remove the bucking bar from the rivet pin]*	0.5	56.5	58.0	1.5																
	op-14	M	QU	*[Perform visual control of the riveting]*	0.0	58.0	61.0	3.0																
	op-15	C	-	Instruct Operator A to move on to the next rivet	0.0	61.0	63.0	2.0																

[text] - operation **NOT** present in every cycle
text - operation present in every cycle
pneumatic hammer activated (**NOT** in every cycle)
pneumatic hammer activated (in every cycle)

Legend:

Types of actions:
- **C** Point communication (command or advice)
- **H** Operator handles parts
- **W** Wait
- **M** Operator moves

Value added activities:
- **TR** Transformation
- **QU** Quality
- **CO** Complementary
- **PA** Passivity

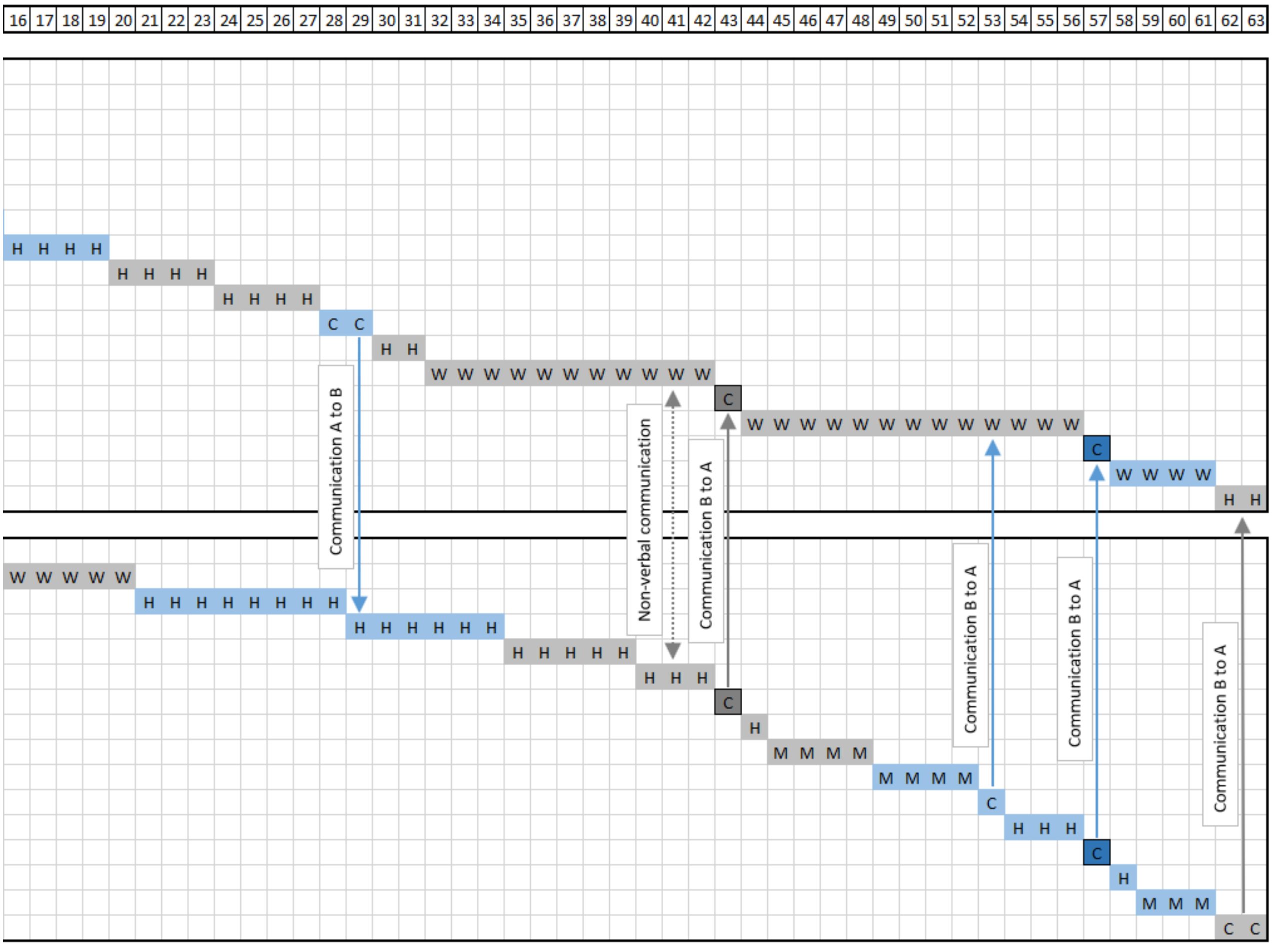


Figure 53: Task analysis chart for the float assembly

3.4.2 Ergonomics

This paragraph is intended to provide a justification as to why the replacement of one of the human operators with a collaborative robot is desirable in a percussive riveting context, from an ergonomics perspective.

The disorders a worker is at risk of developing as a consequence of being subjected to different levels of physical stress on one or multiple parts of the body are generally known as work-related musculoskeletal disorder (WMSD). WMSDs are body injuries that develop gradually over a period of time and are related to repetitive strain injuries, trauma injuries, motion injuries etc. WMSDs can be induced in any part of the body, but for the present study of interest are the disorders of the hands, arms and fingers. There are a variety of factors that can produce such disorders, but of prime interest for this application are the WMSDs induced by vibratory tools. According to ref. [23] (p. 16), the American National Standards Institute (ANSI) developed a standard, S2.70, which stipulates the acceptable levels of vibration to which the workers are subjected:

- Daily Exposure Action Value (DEAV) – the acceptable daily exposure to vibration, for 8 hours/day: 2.5 m/s^2
- Daily Exposure Limit Value (DELV) – the maximum level of vibration above which workers are expected to have a high risk: 5.0 m/s^2

Similar standards exist in Europe. As described in ref. [24], p. 383, the European legislation equivalent to the US S2.70 standard is the EU Directive 2002/44/EC on human vibration exposure. The values of DEAV and DELV specified by the EU Directive are the same as in S2.70.

One parameter that captures the level of vibration the worker is subjected to is the hand-transmitted vibration (HTV). It is the acceleration level of the tool when grasped by the worker in use. Typical symptoms associated with long exposure to high levels of HTV are: tingling, numbness and finger blanching, pain in response to cold exposure, reduction in grip strength and finger dexterity.

For workers performing percussive riveting, two main sources of vibration can be identified:

- The vibration induced by the riveting hammer
- The vibration transmitted by the bucking bar

Both tools require direct, physical contact with the worker's hand. The study documented in ref. [24] identified the levels of vibration at the interface (worker hand – riveting hammer) and (worker hand – bucking bar). These values are shown in Table 7.

Table 7: Levels of vibration felt during percussive riveting - ref. [24]

Location	Bar type	Weighted (m s^{-2})		Unweighted (m s^{-2})	
		Bar	Hammer	Bar	Hammer
Lab	Steel	5.1	6.7	86.1	59.6
	Tungsten	3.9	6.8	52.4	59.5
	Dampened	3.4	6.7	68.7	59.4
Workplace	Steel	10.3	6.7	131.6	41.3
	Tungsten	5.8	8.2	64.1	43.9
	Dampened	7.4	9.2	131.0	48.7

The study was conducted both in a laboratory and in real, industrial conditions (workplace). Three types of bucking bars have been tested – a steel bucking bar, a tungsten bucking bar and a steel, dampened bucking bar.

The vibration felt by the worker is the vibration weighted for frequency (the third column in Table 7). It can be seen that in most cases, the vibration felt at the interface with the riveting machine (hammer) is higher than the vibration felt at the interface with the bucking bar, with one exception. Unfortunately, this exception is the most relevant, as the measurement is performed in a real industrial environment, with a simple, steel bucking bar, as it is used in the majority of cases for the percussive riveting. Also, it can be seen that all the measurements performed at the workplace reveal vibrations in excess of 5.0 m/s^2, the DELV indicated in the ANSI S2.70 standard. The vibration transmitted to the worker is, therefore, of great concern.

The study reported in ref. [22] indicates that the level of vibration felt by the worker holding the bucking bar is not only a function of the type of bucking bar, but also a function of the feed force level. The feed force is the force with which the worker pushes on the bucking bar, in a static condition.

Figure 54 gives the level of vibration for five different bucking bars and for three levels of feed force.

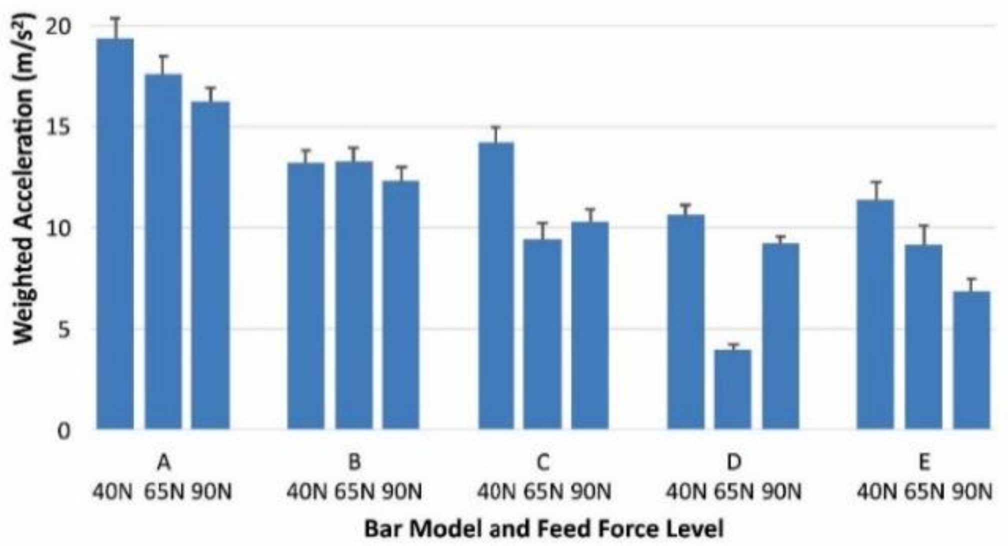


Figure 54: Levels of vibration felt in the bucking bar during percussive riveting - ref. [20]

Bucking bar A	- traditional cold-rolled steel bar
Bucking bar B	- tungsten alloy bar, with the same size and shape as bar A
Bucking bars C, D, E	- bars with spring-damper configurations

What is of interest in Figure 54 is not the actual value of the vibration, but the correlations between the vibration and bar type and vibration and feed force. It can be seen that for traditional bucking bars (as bar A), it is more beneficial to increase the feed force as it reduces the level of vibration. Although the vibration problem is ameliorated, other types of problems arise – muscular stress – especially for awkward positions driven by the difficult accessibility of the assembly. The study reported in ref. [23] investigates the level of vibration the worker feels in different regions of the arm, namely at hand and elbow levels – see Figure 55.

As for the previous studies, multiple types of bucking bars have been investigated:

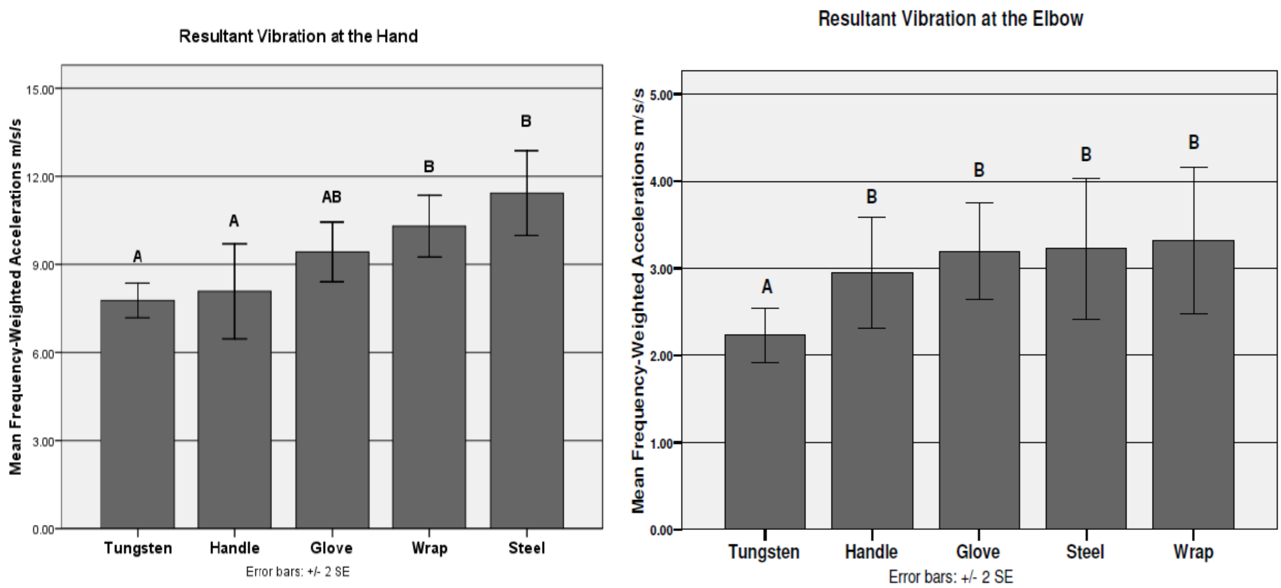


Figure 55: Levels of vibration felt by the worker holding the bucking bar - ref. [22]

- A traditional steel bar
- A tungsten bar, the same size and shape as the steel one
- A steel bar with a gripping handle
- A steel bar with a rubber-like wrap
- And a simple steel bar held in hand with thick rubber gloves

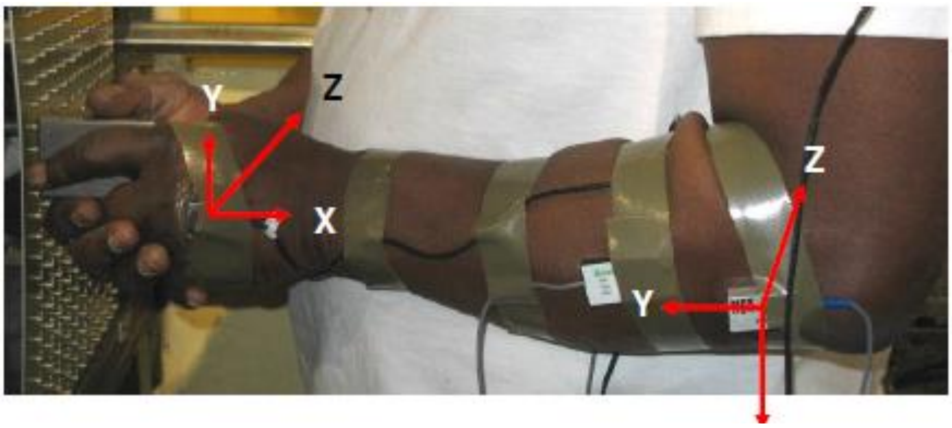


Figure 56: Setup for arm's vibration measurement - ref. [22]

The levels of vibration are actual levels measured with accelerometers positioned at hand and elbow level – see Figure 56.

Once again, the level of vibration at hand level for all bucking bar configurations is in excess of the DELV parameter indicated in the standard. As in the previous studies, the tungsten bar transmits the lowest level of vibration, while the steel one transmits the highest one.

Although the tungsten bars seem to be favored by all existing studies, these are not really used in industry due to the high cost of the material. Instead, steel bars are widely used in the aerospace industry across Europe and the US.

The vibration transmitted through the bucking bar also has a negative impact on the elbow and even shoulders, especially when the vibration's frequency is low. The negative impact is amplified by the need to grip the bar, which necessitates increased muscle force.

Different studies on the ergonomics of riveting, as the ones cited in ref. [23], p. 19, suggest that the grip force for a given bucking bar is affected by vibration: "muscle responses were greatest at frequencies where grip force was affected, indicating that the tonic vibration reflex (a sustained contraction of the muscles caused by vibration activation of the muscle spindles) was likely the cause of increased grip exertions".

Among the disorders associated with increased muscle stimulation for long periods of time and in a vibration-dominated environment one can identify (as reported in ref. [23]):

- an increase in mechanical impedance (the hand-arm's resistance to movement or vibration)
- reduced circulation of blood in the fingers and reduced finger temperature
- fatigue exacerbation as the hand-arm system stiffens
- higher stresses on the anatomical structures of the hand-arm system and obstruction of peripheral circulation
- an inability of the muscle fibers to maintain contraction, resulting in fatigue
- alteration of force control which results in an increase in force exertion, force variability, and tendon stress
- negative influence on the neurological network by stimulating sensory receptors within the cutaneous, muscular, and articular structures and its ability to affect spinal reflexes

In addition to the impact of vibration on hand-arm system, for the particular case of the float assembly (but equally applicable to the assembly of other subcomponents), the posture of the worker has a potential negative influence on his/her health. Given the complex shape of the float, the worker holding the bucking bar is required to stay for long periods of time in difficult, unusual positions. This might have a negative influence on the arms, legs (as he/she needs to stand, often balancing the weight of the body on only one leg) and, maybe the most important, on the spine.

3.5 User requirements collection and stakeholder feedback

3.5.1 Results

3.5.1.1 Use Case Analysis

Following the use case analysis and the interviews, a set of user requirements were identified and refined. Thus, the user requirements were formulated as "The user needs [...]", "The user wants [...]" or "The system shall [...]", format suggested by Sommerville (2011). Further, a coding system will be developed in the form of various categories, whereas each requirement will be assigned to one category, thought to be the most relevant.

The user requirements have been integrated in a prioritization matrix (see Appendix C), with the purpose to show which the most important requirements are that the robotic solution needs to meet. The prioritization tool considers three perspectives: the value for the end user, the customer and the product development perspective, having the following ranking criteria:

- End-User Value:
  - High Usability - Defines if the implementation of a requirement would have a negative or positive impact on usability.
  - Intuitivity - Tells how the implementation of a requirement affects the intuitivity of using the system.
  - Added Value - Defines the value a requirement will bring to the end-user.
- Customer Perspective:
  - Low Costs – Defines in which degree the implementation of a feature would maintain a low cost.
  - Added Value – The value a requirement would bring for the customer.
  - Low Risk - Defines in which degree the implementation of a feature would maintain a minimal risk.
- Development Perspective:
  - Technology Readiness Level (TRL) - The scale expresses if the technology is advanced enough for a requirement to be implemented in each case.
  - Feasibility - Shows in which degree the implementation of a requirement is feasible within the project framework.
  - Integrability - Defines how easy is for every requirement to be integrated into the robotic system.

Each criterion will be weighted, the end user and the development perspective receiving each 35%, while the customer perspective has a total of 30%. This is important, as the perception of End-User is of focus, because s/he is the one directly collaborating with the robotic solution, while from the development point of view, it has to be possible to build a solution to meet the user requirements. The results of the prioritization will be used for the system specifications and the updated results will be presented in D2.2 in M24.

3.5.1.2 Stakeholder Questionnaire

A stakeholder's workshop was organized at the European Robotics Forum 2019, where the CoLLaboratE use cases and industrial scenarios were discussed. The questionnaire was distributed to participants together with project information and a use case overview. The questionnaire was also shared on social media and selected contacts were invited to fill it in. The questionnaire was also distributed during a workshop session on Physical Human-Robot Interaction: a design focus at the International Conference on Robotics and Automation (ICRA)

2019. Until now, 7 answers have been received (see Figure 55) and minimum 20 are required to be able to draw conclusions. Thus, the questionnaire will be kept open until the weighting of the user requirements is done. The focus for the questionnaire is quality over quantity, therefore more specifically selected contacts from industry will be invited to fill in the questionnaire in the next months. Once the weighting of the user requirements is done, the questionnaire will be analyzed, so the results between the user requirements and the questionnaire can be compared. The findings will be presented in D2.2 in month 24.

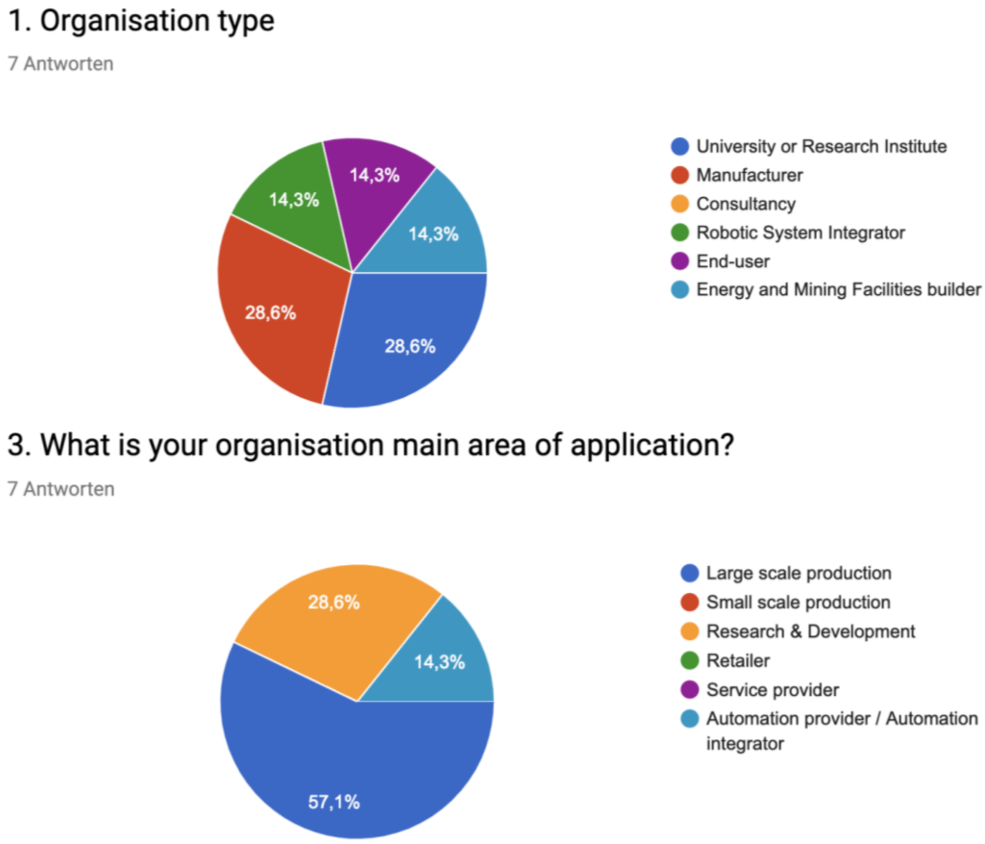


Figure 57 Stakeholder Questionnaire results

4 Final Considerations

4.1 Feedback from Advisory Group

The content of the deliverable has been shared before the submission with the CoLLaboratE's advisory group. In a web meeting of the involved partners with the members of the advisory group, the deliverable was presented in details and an open discussion was initiated afterwards.

The feedback that was received from the members of the advisory group during the meeting, was properly documented and shared to all CoLLaboratE's partners for further considerations that will be made in the following phases of the project. For D2.1 in particular, a further revision and implementation is planned at month 24 (D2.2). Before D2.2 one or more meetings with the participation of the advisory board will be done to keep the experts updated with the refinements of the use cases and of the applied/applicable methodologies identified.

From a high level analysis of the feedback provided:

- the content of Chapters 1 and 2 was considered satisfying. Particular attention and approval was given to the use of the Spaghetti Chart and MTM tools as useful guide for the workplace organization;
- most of the comments concerned specific suggestions and hints for the concept solutions described in the Chapter 3 as description of the Use-Cases. All these comments were rather specific and will be considered later during the implementation phases of the use-cases;
- the suggestions were mainly related to work-place optimization of the final solution to further improve the application efficiency and effectiveness;
- warning was given on the importance of the manipulating end-effectors not to hinder the final applications;
- discussion was done on the possibility to increase performances by the addition of more robots in the workcells;
- considerations on the expected benefits from HRC were done to compare a proposed collaborative application to a fully automatic alternative for the workcell.

4.2 Conclusions

The Deliverable 2.1 is successfully collecting what the project CoLLaboratE developed in order to perform a complete and successful description of use-cases in collaborative environment. For this purpose the structure of chapters has been defined as followed:

Chapter 1: introduction to the description of generic requirements and safety requests that apply to Human Robot Collaboration in the reference industries;

Chapter 2: Description of criteria and requirements that are suggested and useful for the description and understanding of collaborative Use-Cases

Chapter 3: description of the four reference use-cases at public level. Other more detailed descriptions containing data required in Chapter 2 that are considered confidential by the partners are provided as partnership internal and confidential information.

Some of the information defined in Chapter 2 have not been provided in this contest but will be provided in D2.3.

The deliverable D2.1 includes also a copy of the open online questionnaire that have been promoted by the CoLLaboratE project at the European Robotic Forum 2019 in Bucharest related to high level user requirements, the analysis of the collected results will be presented in the updated version (D2.2 at M24). The results are preliminary since the questionnaire is still available online and the analysis will be updated in the D2.2 at M24.

This deliverable is going to be shared with the projects stakeholder committee and the feedbacks will be integrated in D2.2 as well.

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APPENDICES

APPENDIX A – USER REQUIREMENTS INTERVIEW QUESTIONS

Identify problems

1. Briefly describe the use case suggested for the CoLLaboratE project
2. Related to your use case, what problems do you run into in your day-to-day work? Is there a standard way of solving it, or do you have a workaround? (*Helping questions: Why is this a problem? How do you solve the problem today? How would you ideally like to solve the problem?*)

The user environment

1. Who will be the users of the new robotic solution?
2. What level of education or training do the end-users / operators have?
3. What computer skills do the users have and what technical platforms do they use today? (Helping questions: Give examples, and for what they are using it. How much they are using it?)
4. What other systems does the organization use today that the new robotic solution will need to link to?
5. What are your expectations regarding the solution's usability?
6. What training needs do you expect for the future robotic solution?
7. What kind of documentation do you expect?

Identifying non-functional requirements

1. What are your expectations for the robotic solution availability and performance?
2. What are the organization's support and maintenance requirements?
3. Who do you expect to manage the future solution support and maintenance?
4. What are your organization's safety requirements?
5. What are your organization's requirements for re-configuration?
6. Are there any legal requirements or other regulatory requirements that need to be met? (*other than the known standards*)
7. Can you think of any additional requirements that we should know about?

APPENDIX B – USER REQUIREMENTS FOR COLLABORATIVE ROBOTS QUESTIONNAIRE

User Requirements for Collaborative Robots

This questionnaire is part of the EU project called CoLLaboratE, which focuses on how industrial robots learn to cooperate with human workers for performing new manufacturing tasks, with a special focus on the challenging area of assembly operations. In human-robot collaboration it is usually the human who states the goal, while it is the task of the robot to assist the human and take on the human's intention as its own and therefore as the joint intention of all.
All of the following questions will be related to collaborative robots. Thank you for your help!

* Required

General Information

This section refers to information about the organisation you're representing.

1. **1. Organisation type** *
Mark only one oval.
   - ◯ University or Research Institute
   - ◯ Manufacturer
   - ◯ Consultancy
   - ◯ Other: ____________________

2. **2. Country** *
____

Current Situation

This section follows the current situation in your organisation and how is your work performed. If you represent a University or Research Centre, please think of the use case /s that you are currently working on.

3. **3. What is your organisation main area of application?** *
Mark only one oval.
   - ◯ Large scale production
   - ◯ Small scale production
   - ◯ Research & Development
   - ◯ Retailer
   - ◯ Service provider
   - ◯ Automation provider / Automation integrator
   - ◯ Other: ____________________

4. **4. How is the work performed in your organisation?** *
Mark only one oval.
   - ◯ Manual
   - ◯ Automatized
   - ◯ Combined
   - ◯ Other: ____________________

5. **5. To what extent have you automatized your processes in the organisation?** *

Mark only one oval.

- Many applications
- Some applications
- Only for testing purposes
- No applications

6. **6. Which of the following have you used for automatising your processes?** *

Check all that apply.

- Robots
- Industrial machines
- IoT solutions
- None
- Other: ____________________

Your opinion about collaborative robots

This section refers to a situation where your organisation would adopt collaborative robots in automatising your processes.

7. **7. In which area do you think collaborative robots could improve your organisation?** *

Check all that apply.

- Productivity and cost reduction
- Ergonomy (e.g. Employee's health, avoid Heavy lifting)
- Quality
- Safety
- Lead time improvement
- Flexibility and Innovativeness
- Other: ____________________

8. **8. Which do you think are the main impediments in adopting robots to automate your processes? (please check all that apply)** *

Check all that apply.

- Employee's acceptance
- Technical capacity
- Initial investment and Return on investment
- Current technology maturity
- Technical Risk, Required maintenance and downtimes (e.g. robot stopping to work requiring maintenance)
- Safety
- Other: ____________________

9. **9. Please rate the following features a collaborative robot should have if implemented in your organisation:** *
Mark only one oval per row.

	Crucial	Important	Useful	Not Important	Not Sure
Learning by human demonstration	◯	◯	◯	◯	◯
Human intention estimation & gesture recognition	◯	◯	◯	◯	◯
Ergonomics performance monitoring & adaptation to the worker	◯	◯	◯	◯	◯
Human awareness & safety	◯	◯	◯	◯	◯
Self-learning & adaptation in collaborative operations (e.g. assembly, handling, transfering)	◯	◯	◯	◯	◯

10. **10. Please rate the following CoLLaborateE project visions:** *
Mark only one oval per row.

	1 (Not Important)	2	3	4	5 (Very Important)
Adaptive robot control in collaborative tasks with physically coupled actors	◯	◯	◯	◯	◯
Collaborative behaviour primitives	◯	◯	◯	◯	◯
Human Touch Recognition and Classification	◯	◯	◯	◯	◯
Detection of Human Intentions for AGVs and Professional Gesture Recognition	◯	◯	◯	◯	◯
Learning from human demonstration (visual and/or kinaesthetic)	◯	◯	◯	◯	◯
Autonomous Assembly Policy Learning and Policy Improvement	◯	◯	◯	◯	◯
Multimodal Learning of Assembly Tasks	◯	◯	◯	◯	◯
Dynamic active constraints construction and enforcements for human safety during HRC	◯	◯	◯	◯	◯
Monitoring the Ergonomic Performance of the Operator	◯	◯	◯	◯	◯
Efficient Production Planning Optimising the Utilisation of Human and Robotic Resources	◯	◯	◯	◯	◯
Fast Adaptation of Co-Production Cell through Reconfigurable Hardware Design	◯	◯	◯	◯	◯

Future Considerations

11. **11. Please describe in a few words what a collaborative robot should do if implemented in your organisation**

____

____

____

____

____

12. **12. Can we contact you for further questions about this topic? (this would be max. 2 times on the duration of the project)** *

Mark only one oval.

- ⬭ Yes
- ⬭ No

13. **13. Would you like to be involved in the CoLLaboratE project as part of the Advisory Board?** *

Mark only one oval.

- ⬭ Yes
- ⬭ No

14. **14. Name**

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15. **15. E-mail address**

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APPENDIX C – USER REQUIREMENTS LIST

ID	Source (Use case)	User Requirement
UR_1	CRF	The robotic solution shall be accessible for the operators
UR_2	CRF	The robotic solution shall be intuitive
UR_3	CRF	The robotic solution should be easy to use for any level of experience among the operators
UR_4	CRF	The user needs an HMI which communicates in their local language
UR_5	CRF	The user needs an HMI which uses as less words as possible, preferably graphical
UR_6	CRF	The user needs specific training in relation to how to CoLLaboratE with the robot
UR_7	CRF	The user needs all the essential information about using the robot to be visible at any moment during their work
UR_8	CRF	The user needs to have all the important information about using the robot, available on site
UR_9	CRF	The robotic solution shall be available at any time, having a 100% availability
UR_10	CRF	The user needs to be able to perform the usual maintenance procedures in house
UR_11	CRF	The user needs to have external support and maintenance available at any time for more serious problems related to the robotic solution
UR_12	CRF	The robotic system shall comply with the existing standards for collaborative robots.
UR_13	CRF	The system shall provide the user with a risk assessment report
UR_14	CRF	The robotic solution shall be able to send feedback to the operator in a collaborative situation in a collaborative situation
UR_15	CRF	The robotic solution shall be able to receive feedback from the operator
UR_16	CRF	The robotic solution should be certified
UR_17	CRF	The user needs an adaptable and flexible solution, which can handle different objects
UR_18	CRF	The system shall not gather data from the operators, unless it is safety related
UR_19	CRF	The system shall be able to ask for the operator's identification
UR_20	CRF	The system shall be able to handle heavy payload (a windshield)
UR_21	CRF	The users need a solution which will help with their ergonomics.
UR_22	CRF	The solution shall be able to change the position of the handled object, depending on the operator's needs
UR_23	CRF	The robot shall learn from the user in order to be proactive to the next steps
UR_24	CRF	The robot shall be able to adapt to each operator that uses the work cell
UR_25	CRF	The robot shall be able to continuously adapt to the operators, in a smooth way
UR_26	ROM	The robot shall be equipped with a human machine interface
UR_27	ROM	The robot shall send information to the human operator about the quality of the ongoing activity
UR_28	ROM	The robot shall be able to determine the quality of the performed activity (rivet)
UR_29	ROM	The user needs an easy to use interface available for all operators, no matter of their experience
UR_30	ROM	The user needs a light training for technicians for how to communicate with and understand the robot
UR_31	ROM	The user needs the robotic solution to communicate every step of the collaborative process
UR_32	ROM	The robot shall provide quick recharge and long operating time for the battery

UR_33	ROM	The user needs easy and quick maintenance for the robotic solution
UR_34	ROM	The robot shall be able to adjust to different applications
UR_35	ROM	The user needs a fast tool exchange and reconfiguration / reprogramming
UR_36	ROM	The robot shall be able to manipulate heavy payloads
UR_37	ROM	The user needs a verbal feedback from the robot
UR_38	ROM	The system shall be able to receive verbal feedback from the operator
UR_39	ROM	The solution shall show a picture of the performed activity (riveting) for the operator to analyse
UR_40	ROM	The user needs visual documentation of how to use the robot
UR_41	ROM	The user needs affordable maintenance of the robot (costs, time, etc.)
UR_42	ROM	The user shall be able to do the basic maintenance in house
UR_43	ROM	The required maintenance operations on the robotic systems shall be minimum during its expected life
UR_44	ROM	The robotic system shall be highly adaptable to percussive riveting of multiple types of structures
UR_45	ROM	The main language of communication between the robotic system and the human operator(s) shall be English
UR_46	ROM	The robotic solution shall be able to perform specific operations, allowing the operator to adjust the time intervals
UR_47	ROM	The robotic system shall be capable of displaying information to the human operator both in SI and US/UK units.
UR_48	ROM	The robot shall be able to perform specific tasks without the human operator
UR_49	ROM	The robotic system shall be capable of independently identifying the optimal way of moving in a new position to facilitate the action the operator wants to perform
UR_50	ROM	The robotic system shall be mobile – its position on ground shall be adjustable.
UR_51	ROM	The robotic system shall have a life expectancy of more than 5 years of continuous operation (excluding the battery recharge time, if any).
UR_52	ARC	The robotic system shall handle multiple electronic boards.
UR_53	ARC	The robotic system shall be able to pick electronic boards from a box and place them on predefined locations on the TVs
UR_54	ARC	The robotic system shall be able to place the objects on a continuous conveyor belt
UR_55	ARC	The robotic system shall perform at least as fast as the current cycle time
UR_56	ARC	The main language of communication between the robotic system and the human operator(s) shall be Turkish
UR_57	ARC	The users need a simple graphical user interface
UR_58	ARC	The user needs the robotic solution to have additional communication, if the robot should exchange different tooling or grippers.
UR_59	ARC	The users need a backup plan if the robot needs maintenance, as the production line cannot being stopped for that long
UR_60	ARC	The users, who are robot representatives, needs a detailed training
UR_61	ARC	The users, who are the daily operator, needs a simple training for basic interaction
UR_62	ARC	The users shall have easy access to the documentation
UR_63	ARC	The users need documentation, which is easy to read, and is most preferred by videos
UR_64	ARC	The users shall be able to access documentation from their smartphone or the operating tablet

UR_65	ARC	The maintenance team shall a detailed documentation so they can repair the general problems in the robotic system
UR_66	ARC	The robotic system shall be able to send performance data
UR_67	ARC	The robotic system shall be performing for 14 hours a day
UR_68	ARC	The robotic system shall be able to perform the same operation as the current operation
UR_69	ARC	The robotic system shall be able to be reconfigured easily according to the objects it is handling
UR_70	ARC	The user (robotic developers) shall be able to add additional programs to the robot, so new configurations for new objects can be added
UR_71	ARC	The robotics system shall be compliant with EST standards
UR_72	KOL	The users need simple training
UR_73	KOL	The robotic system shall be easy to use
UR_74	KOL	The robotic system shall by manageable by every worker in the production
UR_75	KOL	The users need a graphical and simple UI so the users can easily overview the steps of the process
UR_76	KOL	The robotics system shall be able to pick small objects from a slowly moving conveyor belt and place them properly in specific fixtures
UR_77	KOL	The robotics system shall be performing 24/7
UR_78	KOL	The users, who are the technologist, shall be able to service and maintain the crucial parts of the robotic system
UR_79	KOL	The robotics system shall communicate properly to the users, so the user gets the proper signal at the proper moment (if something happens)
UR_80	KOL	The robotics system shall be able to be reconfigured to manipulate different variations of the same product category (small dimensional changes)
UR_81	KOL	The users need to be able to take over the process of the robot, if the robot breaks down
UR_82	KOL	The robotic system shall comply to the ordinary safety standards for collaborative robots