Collaborative robotics adoption: KITT4SME report 2022 in collaboration with TRINITY Robotics

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KITT4SME report 2022/2023 in collaboration with TRINITY

Collaborative robotics adoption: the experience from the BRILLIANT project

INVOLVED PROJECTS

The **KITT4SME** project is developing scope-tailored and industry-ready hardware, software and organisational kits for European SMEs and mid-caps. The aim is to deliver these as a modularly customisable digital platform that can seamlessly introduce artificial intelligence in their production systems. The project will ensure that the kits are widely distributed to a wide audience of SMEs and mid-caps in Europe. What is more, the seamless adoption of the kits will be facilitated through the integration of legacy factory systems like ERP, as well as IoT sensors and wearable devices, robots and other factory data sources.

More info at www.kitt4sme.eu.

The **TRINITY** project is strengthening Europe's position by creating a network of multidisciplinary and synergistic local digital innovation hubs focused on agile production that will include researchers and companies implementing solutions. The network will also offer consulting services for business planning and accessing financing, propelling Europe to the forefront of agile manufacturing and robotics.

More info at www.trinityrobotics.eu.

BRILLIANT is a project funded through an open call of the TRINITY project which aims at developing a proof-of-concept of a collaborative solution for artisanal manufacturing in the Ideal-Tek's production lines dedicated to tweezers production. Specifically, the manufacturing operations that are being re-engineered towards the combination of the flexibility and dexterity of humans with repeatability of cobots are: welding, tweezers aligning, tail grinding, cleaning of welding spots.

More info at https://brilliant.spslab.ch.

COLLABORATIVE ROBOTICS

Back in 2011, Mark Lewandowski, the head of Procter and Gamble's Machine Controls Technology division, showed up at the Robotics Industry Forum saying[1]:

"Guys, I am very willing to buy robots from you now, but you don't have what it takes! The robots that Procter and Gamble needs have to satisfy the following requirements:

- *Smaller footprint and larger workspace;*
- *Low integration costs;*
- *Possibility of a modular integration approach;*
- *Simple installation with integrated basic functions;*
- *Easy for the robot to talk to other components;*
- *Low price;*
- *Collaborative meaning without security protections or fences."*

From that moment on, Procter and Gamble became one of the pioneers and supporters of collaborative robotics to tackle tedious workflows and repetitive tasks in dirty or low ergonomic environments. In 2018, the company already had between 150 and 200 collaborative robots in use at various plants, mainly for pick-and-place, palletising and boxing robots. Meanwhile, safety standards for collaborative robotics were spreading within the manufacturing industry. Collaborative robots, also known as cobots, are the more accessible and approachable descendants of traditional industrial robots. **They are usually smaller, less expensive, and, thanks to intuitive software, more accessible for non-experts to program**. Cobots help improve safety and health while addressing efficiency, scale, and other production requirements. **Collaborative robotics is intended to complement traditional robotics by increasing the degree of workers' involvement. Without fences, the worker and the cobot can share space and processing**. Collaborative robots are suitable for certain tasks that can only be automated at a high cost or for vertical applications that are not flexible at all. An example is an assembly, which, with traditional robotics, requires expensive fixtures, tools, grippers, and a corresponding amount of programming. To the contrary, by using a collaborative robot, a higher return on investment can be easier and faster achieved, thanks to its intrinsic flexibility and to the fulfilment of automation gaps with human capabilities and skills. Thus, collaborative robots represent a good opportunity for small to Medium-size Enterprises (SMEs). The lower price point and the smaller initial investment of cobots, compared to traditional robots, naturally make for a better ROI. Their quick integration and flexibility allow SMEs to reduce downtime and non-productive activities during production hours.

With the widespread adoption of collaborative robots, new possibilities for designing tasks that are 'side-by-side' or 'face-to-face' with the operators have appeared. Collaborative robots can be used in various processes, such as material handling, assembly, dispensing, machine tending with different levels of complexity and cooperation (coexistence, sequential collaboration, cooperation, reactive collaboration)[2]. Advanced forms of collaboration enable more significant benefits and performance, while complexity is often a side effect required to meet process and performance constraints.

[1]Samuel Bouchard (Robotiq CEO). The Robots that Procter & Gamble Dream About. 2011

[2]Fraunhofer Institute For Industrial Engineering. Lightweight robots in manual assembly - best to start simpLy!. 2016

OUR SURVEY

A survey has been conducted to investigate the current adoption of collaborative robotics. The survey has been delivered via different KITT4SME and TRINITY dissemination channels. Moreover, regional industrial associations and innovation hubs have been involved. The results included 39 responses; 19 from end-users and 20 from system integrators from 17 different countries in Europe.

Of the end-users, 47% has already a cobot operating in their production system and 41% are willing to buy it in the next few years. A similar statistic also involves the system integrators: 45% of them have already developed at least a collaborative robotics installation, while 35% have not installed a cobot, yet but it is willing to do so. Finally, only 20% of them are not interested in the technology thinking that its impact will be negligible.

The survey highlighted that three of the top five obstacles and barriers are classified as economic. These are: high initial investment, lack of budget, and high implementation costs. The other two main barriers are unproven impact on production performance and lack of resources. The former leads to the conclusion that existing applications are not able to achieve the expected production performance, or that there is a lack of success stories and use cases to prove the effectiveness of collaborative robots. The lack of use cases is also due to the fact that collaborative robotics has emerged as a new technology in the last few years and it has only recently reached its maturity and attractiveness. The lack of resources may be related with both the lack of budget and the lack of skills. As confirmed by the economic barriers, despite cobots being cheaper than traditional robots and automation, the investment is still an obstacle. Without the proper budget dedicated to process and production line innovation, a company cannot adopt a collaborative robot. Figure 1 provides an overview of the assessment provided by the 39 respondents on the 10 main identified barriers.

41%

of the respondents that do not own a cobot is willing to buy a one in the next 3 years.

45%

of system integrators have already participated in the installation of a cobot.

47%

of end-users has an operating cobot.

Lack of resources and high initial investment

are considered the main barriers for the introduction of collaborative robotics.

Participate in the survey!

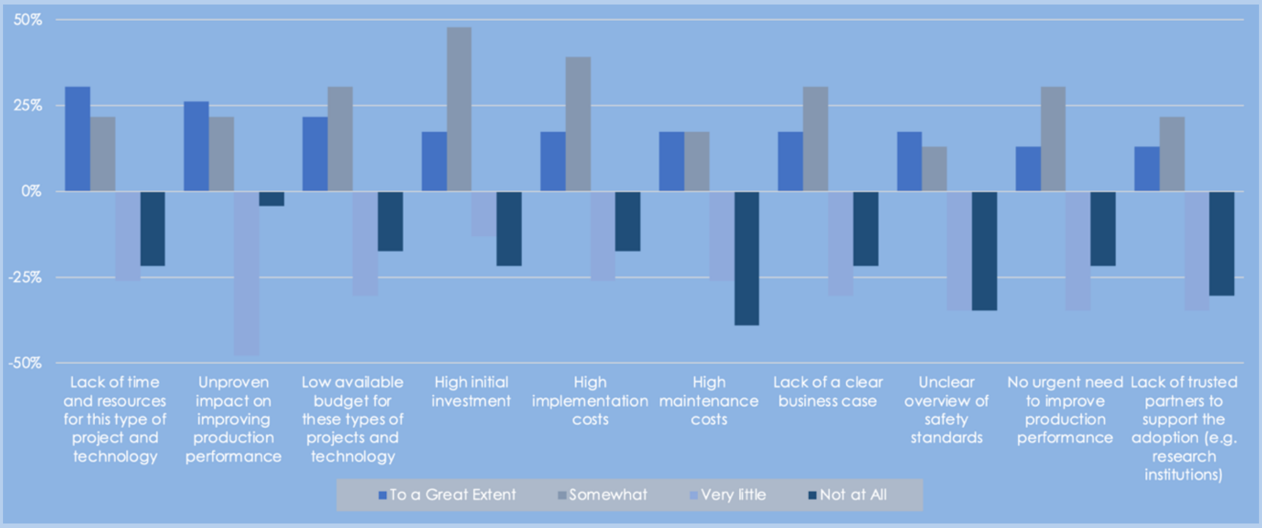


Figure 1 Main barriers towards collaborative robots adoption

A collaborative robot has the potential to be employed in a wide range of different applications, including assembly, material handling, machine tending, finishing, welding, dispensing, quality inspection and machine tending.

The survey explored these applications by asking end users what tasks cobots are currently used for or will be used for in the future. Similarly, system integrators were asked for which applications they have installed cobots in a production system. The result shows that the majority of respondents use cobots in the areas of material handling and quality control. As far as material handling is concerned, cobots are mainly used at the end of the production line in the packaging and palletizing processes. Survey results indicate that the cobot is also used for assembly, finishing and welding applications. It is surprising that assembly, the operation on which it is possible to find many research works, is positioned only third among the applications from the respondents. Figure 2 provides an overview of the applications where respondents applied and deployed cobots (between the respondents there were end-users with multiple cobots, and system integrators having realised multiple installations).

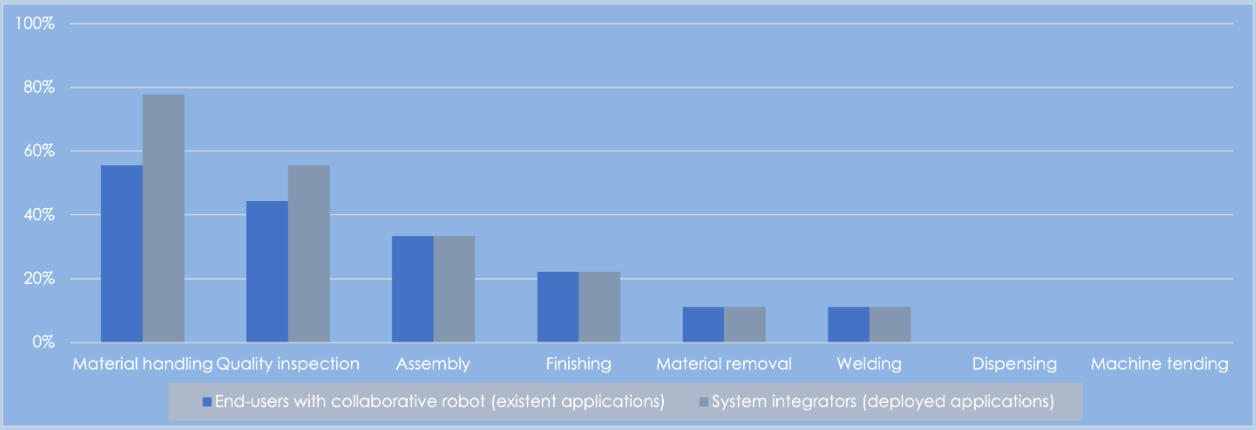


Figure 2 Applications in which collaborative robots are used and deployed

The previous results confirm the existing knowledge gap on how to properly exploit the cobot's capabilities in a manufacturing environment. They also show a discrepancy between desired applications and actually installed ones. For instance, end users express great interest in developing applications for assembly in the future. Instead, the high level of interest in integrating the robot into material handling and quality inspection activities is confirmed. In general, the histogram shows that the responses are more evenly distributed among the possible applications. This tendency can be seen in Figure 3. Here, the expectations of both end users who already have a cobot and those who plan to use it in the near future were collected.

Material handling

is the application where the majority of cobots are deployed.

Assembly

is the application more desired in the future.

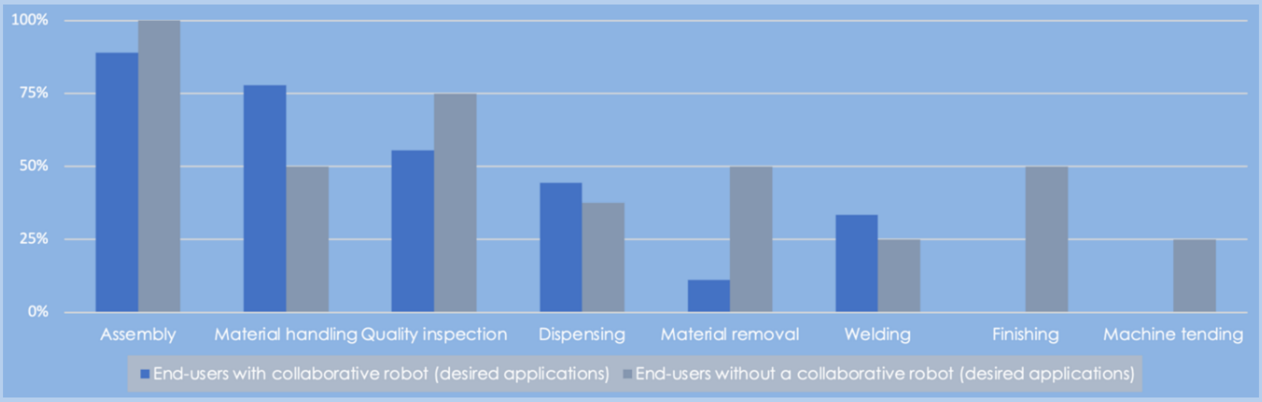


Figure 3 Desired applications for future collaborative robotics deployment

Moving into the human side of collaborative robotics, manufacturing companies are increasingly interested in improving their social sustainability and the well-being of their workers. Respondents state that they are trying to achieve these goals also through collaborative robotics, reliving workers from repetitive, alienating, and low-value-added tasks. This aspect can be seen in Figure 4, in which respondents highlight that the main goal they expect to reach from introducing collaborative robotics in the production line is to improve worker well-being. Relieving workers of unergonomic and repetitive tasks can reduce the risk of health problems, but also increase worker retention by assigning them value-added and satisfying tasks. Respondents also agreed that collaborative robotics can increase the quality of the process. Few also emphasised that they have used cobots to reduce cycle time. Cobots are not believed to work faster than workers. However, they are tireless and, when coupled with a worker, can easily reduce process cycle time with a limited investment.

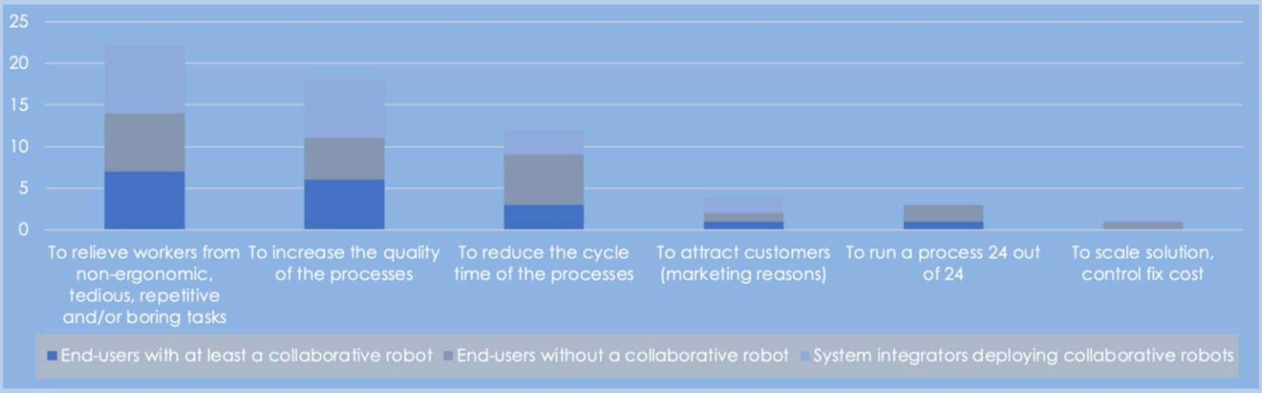


Figure 4 Expected benefits from the introduction of a cobot

The survey investigated more aspects and results. It also includes responses from 35 researchers. **To get more insights contact us at info@kitt4sme.eu**.

OUR GUIDELINES TO ADOPT COLLABORATIVE ROBOTS

Starting from other more general purpose design methodologies, our research team has identified guidelines that can walk researchers and practitioners through the winding roads of this technology adoption.

These guidelines aim to support non-experts in selecting the process to assign the cobot, analysing its characteristics and designing the collaborative work cell. For each step, a series of questions have been formulated to support a deeper analysis of the most relevant aspects to get the most from a collaborative robot. All these guidelines have been defined and applied within the BRILLIANT project, a demonstrator of the European project TRINITY.

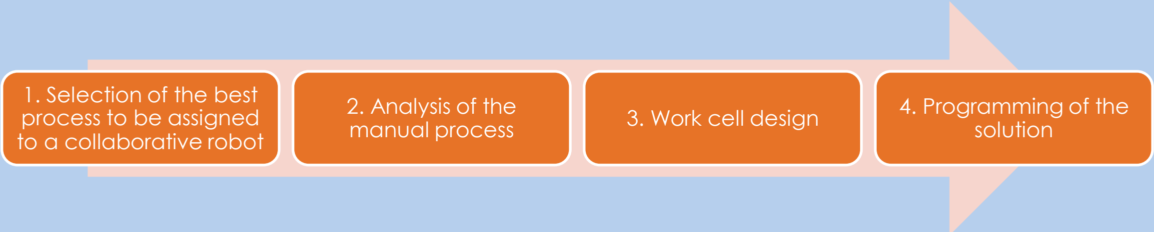


Figure 5 Main phases for cobot adoption

1. SELECTION OF THE BEST PROCESS TO BE ASSIGNED TO A COLLABORATIVE ROBOT

The selection of the right process where to introduce a collaborative robot is fundamental to get the most out of it. In fact, this activity influences both the implementation costs and the Return on Investment (ROI). It is even more relevant if this is the first implementation that the company is realising. When a company decides to undertake the journey towards the adoption of collaborative robotics, it should consider the following points:

- **Complexity does not bring value**. When implementing a collaborative application, it is essential to keep it as simple as possible. Solutions such as computer vision or AI models should only be used when they are the only option and bring more benefits than drawbacks.
- **The plan is almost never followed.** To realise a collaborative application will likely take more time than expected. Many issues will arise during the project, some challenges will be identified from time to time and vendors will fall behind the schedule. To limit all these issues, it is essential to define the specifications of the solution, minimise changes and avoid "nice to have".
- **It will not be easy.** To properly integrate a collaborative robot and to realise an effective collaborative application that achieves the expected results will not be an easy task. Many companies are introducing collaborative robots due to the current hype, to show customers visiting the factory that the company is striving to innovate and optimise the production systems. However, under this premise, trivial applications are usually implemented, which do not require special efforts but do not bring value to the production system, usually showing a negative ROI. Properly deploying collaborative robotics in real industrial processes, bringing value and attempting to move from one to multiple applications requires commitment and resources. Yet, the benefits in terms of performance are incomparable.
- **The trade-off between the short and long term is fundamental for the successful adoption of collaborative robotics in a company.** When a company introduces collaborative robotics into its production system, it must start simple, without trying to do everything at once. This will allow to become confident and familiar with the technology, build skills and experience. However, the first application will hopefully not be the last. Therefore, it is essential that long term applications and other identified opportunities are also considered in order to avoid wasting of resources (e.g., buying a gripper that can be applied in different applications or with different products or using a modifiable or modular workbench, that could cost more than off-the-shelf solutions, but that can be used in more applications).

Salvatore Alivesi, VP of Operations at I-TEK, confesses that *"There is no financial viability for us to buy a cobot if we can't change almost every week the operations it has to perform"*.

Considering all these elements, the first challenge that a company aiming to introduce collaborative robotics has to face is:

In which manual process and/or work cell should a collaborative robot be adopted?

Companies usually tend to choose complex tasks or try to implement sophisticated types of interactions. However, this often ends in failures or creates discouragement. It is recommended to start simple and avoid elements that create complexity like vision systems. It is often assumed that vision systems are the solution to many problems (e.g., for gripping parts, supporting pose estimation) without considering the complexity behind this kind of technology. In many cases everything can be solved with simpler solutions such as well-designed fixtures and feeding systems, drastically reducing both complexity and costs but with the same result. **To select processes that best fit collaborative applications without performing specific and detailed analysis, five main characteristics have to be considered.**

Variability of tasks

A collaborative robot is much more flexible than a traditional robot. It can also work with one or more operators who can perform the most complex tasks, making the cobot capable of handling complex processes and even multiple tasks without the need for advanced equipment. However, it is important to consider if this means that specific end effectors are required for each task, or if multiple tasks can be performed with a single end effector (e.g., pick-and-place and screwdriving). When multiple end effectors are required for different tasks, it is important to consider whether collaborative robotics is indeed the right choice, taking into account the cost, space requirements and changeover time. Collaborative solutions are suitable when the number of tasks to be performed by the robot is limited and/or the tasks are similar to each other.

Guiding questions

Which are the operations the product is subjected to? Does the part need to be grasped or is it processed without lifting it?

How much does the task to be performed change in terms of operations?

How variable is the processing time? Is it constant or does it depend on some factors?

Is the operation performed with single or multiple parts?

Which is the accuracy and repeatability required by the process?

Is the process standardized? Do the differences between the workpieces belonging to the same part number require different processing modes? E.g., upstream processes generate small differences between the parts that require the operator to adapt the operations from time to time.

Is the process characterised by a high number of unexpected events? E.g., out-of-quality workpieces that are identified by the operators.

Productivity

The productivity of a collaborative robot is much lower than that of a traditional robot, and, in many cases, the cobot might even be considered slower than an operator. However, the consistency, ability to work around the clock, accuracy and much lower error rate can make it more efficient than an operator. Moreover, cobot's productivity sums up to the operator's one leading to an overall increased throughput. If the process requires very high productivity to meet the turnaround time of the production flow, the robot may not be the right choice. The collaborative solution is suitable when the cycle time to be maintained is slightly higher than that required by an operator.

Guiding questions

Can operations be performed at the same pace as an operator, or there is the necessity to go much faster?

How many operators are assigned to the process?

Are there any contingencies in the process that need to be addressed and resolved?

How much is the training time for a new operator to complete the task according to the set criteria?

Is the demand for the product constant over the year?

Is the process performed constantly throughout the year?

Product margin

The introduction of a robot, which repeats very quickly and constantly the same tasks, is mainly the answer to increasing the gross profit margin of a product which is characterized by a low-profit margin. Collaborative robots have not been thoughts for this kind of activities as they are much slower than a traditional robot and are more common in activities where the working pace is not the only determinant.

Guiding questions

Does the processed product or product family show high-profit margins?

How much is the value-added provided by the process for the final product?

Batch size/product similarity

The introduction of automation of any kind requires a more or less stable and constant production, with a volume that allows the amortization of fixed costs, since reassigning a cobot is more complex than reassigning an operator. It is true that a collaborative solution is much more flexible than the traditional one, but programming, installation and use on multiple production lines always generate costs that must be taken into account. If the demand for a particular product is not constant over time or the batches are very small and spread over different periods of time, collaborative robotics is not the best solution. However, if the demand is more or less constant and/or the application can be easily adapted to several product lines, a collaborative robot is often the right choice.

Guiding questions

Is there variability in terms of shapes, dimensions, weight, materials, etc. between product types that pass through the process?

Is there variability in terms of shapes, dimensions, weight, materials, etc. between families of products that pass through the process?

Do products arrive in a continuous flow or in batches? Usually, how many products are in a batch?

How often does the product type change?

How many working days are needed to satisfy the yearly demand?

New product releases

The cobot is an automation solution that requires programming and equipment to work. If the product changes very frequently, it is probable that a new part program has to be developed for the new part. If, in addition to the cobot, the application includes workbenches, fixtures, jigs, etc. made for the specific product, the transition from one product type to another could be expensive, reducing the ROI.

Guiding questions

How often a new part/product is introduced in the process?

How often are existing parts/products changed/updated?

Is the change impactful on the characteristic of the part/product?

Figure 6 supports qualitatively in understanding what are the most suiting applications for either cobots, traditional robots or operators. Blue areas identify desirable levels of the characteristics to get the most out of each working methodology while white areas suggest that the process performed in that way could have some limitations in performance.

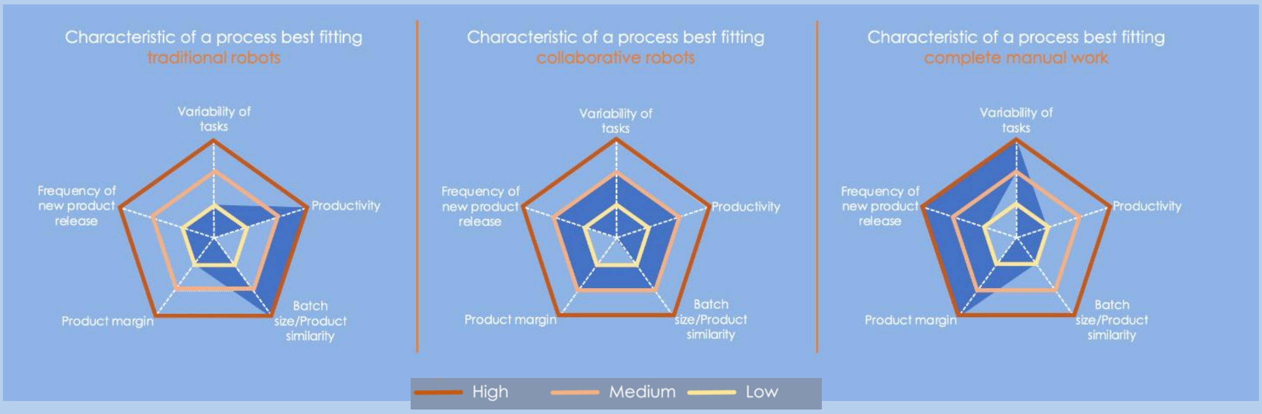


Figure 6 Characteristics of a process suitable for manual work, a cobot or a traditional robot

The BRILLIANT experience

The BRILLIANT project aims to develop a smart, orchestrated and reconfigurable collaborative work cell to reduce adoption barriers of collaborative solutions for SMEs. In particular, it introduces a collaborative robot in Ideal-tek SA, one of the world leading manufacturers and suppliers of precision hand tools and instruments, pushing automation's limits to the highs of the dexterity needed in an artisanal manufacturing process.

To select where to deploy a collaborative robot in the Ideal-Tek production system, the BRILLIANT team has evaluated 17 different processes. Several hours have been dedicated to observe the operations characterising these processes, annotating the collected information and reporting all the relevant considerations. After the classification of each process according to the parameters reported above, welding and polishing have been selected as the most proper processes to start the adoption of collaborative robotics in Ideal-Tek. As reported in Table 1, the assessment has been carried out comparing all 17 processes against the proposed parameters: variability of tasks, productivity, batch size/product similarity, product margin, and new product releases.

Table 1 Process selection assessment

Process	***Variability of tasks***	***Productivity***	***Batch size / product similarity***	***Product margin***	***New product releases***	***Legend*** ***H:*** *High;* ***M:*** *Medium;* ***L:*** *Low;* ***NA:*** *Not Available for confidentiality issues* ***Feasibility assessment (CR: Collaborative Robotics)***
Welding	*H*	*M*	*M*	*NA*	*H*	*It is not the best application for collaborative robotics since the possibilities of collaboration and interaction between the human and the cobot are limited. However, a cobot fits the application due to the limited availability of space, process repetitiveness and the five proposed characteristics.*

Polishing	*M*	*M*	*M*	*NA*	*H*	*The cobot can be introduced to relieve workers from this repetitive activity, allowing the humans to supervise the cell and focus on quality control and finishing if needed.*

2. ANALYSIS OF THE MANUAL PROCESS

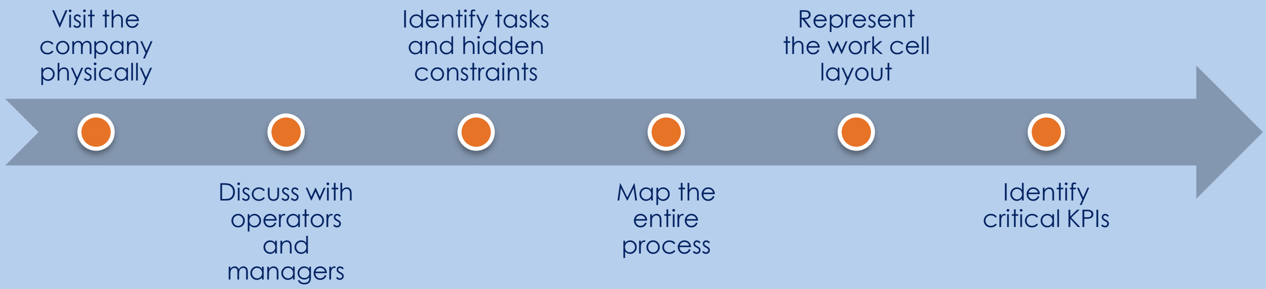
After understanding which processes are suitable to introduce a collaborative robot, it is necessary to analyse them, identifying undesired system performance with existing solutions and detecting negative outcomes which affect productivity and quality, as well as human conditions such as low engagement, health problems or exaggerated workforce turnover. So, now the second challenge that a company aiming to introduce collaborative robotics has to face is:

How should the existing process and work cell be analyzed in order to introduce a collaborative robot? Which are the most relevant elements to consider in this analysis?

This analysis focuses on the tasks that are carried out within the selected process. To have a real and complete understanding of the task, it is essential to physically visit the work cell. This allows, first, to understand the workflow, but also to investigate constraints, issues, problems and challenges that workers are currently facing in the operations. During the visit, it is suggested to take pictures or even make a video involving several complete workflows and, if possible, different workers, so as to observe different approaches and modi operandi and also to identify elements that may have escaped.

The dialogue with operators, process experts and other figures working on the shop floor is the real added value of this activity. Thanks to the experience matured daily, operators are an invaluable source of information. The recommended approach initially involves questioning the production manager about the critical aspects of the analysed process. Then, all the operators should be involved to understand the main issues and challenges that are facing to complete the activities.

During the analysis, it is fundamental to identify constraints and "hidden" tasks. These can be very simple and with low relevance for the workers but fundamental for the process and challenging for the cobot to be performed. These tasks could be, for example, the orientation of the piece in order to facilitate an operation, a visual inspection or the removal of some residues, which are not described in the Standard Operating Procedure (SOP) of the process, but that are carried out by the workers as a subconscious routine. During this analysis, it is also relevant to consider the exceptions and how these are solved (e.g., one part out of 50 requires to be cleaned before the task execution).



Map the entire process

Process mapping helps to capture all the steps (and decisions) made by the worker to complete all the tasks of the process under investigation. A starting point for the process mapping is the Standard Operating Procedures (SOPs), a set of step-by-step instructions that help workers to carry out routine operations. However, an observation of the entire process is still required to verify if the activities match closely what is reported in the SOP.

Since at this point it is already fundamental that the analysis is very detailed, attention should be paid to uncommon or unexpected events that could happen during the processing of the product. Mark the tools that are used, all the resources that are involved, the inputs and outputs of the operations and if changeovers happen during the process. Finally, measure the time and the variability for each operation. The resulting map will give a picture of how things are actually done and represents the starting point for understanding how the collaborative robot can intervene in the activities. To formalise the collected information, it is suggested to use flow charts, BPMN models and/or IDEF0 models.

Guiding questions

Which are the tasks and the operations performed in the process?

Which are the average cycle times and their standard deviations?

Are there waiting times during the process?

Which are the tools, equipment and machines used? Is there a specific tool for each part number?

How much time does each operation last? Is this time subjected to variability?

Which setups are needed?

Is a specific setup required when changing the part number?

Which unexpected events can occur in the process? How are they solved?

Which are the specifications that characterise an in-quality part?

How do parts arrive in the process? E.g., box, jigs, conveyor, …

How do parts leave the process? E.g., box, jigs, conveyor, …

How does the operator or the machine know what to do and when to do it?

Represent the actual work cell layout

One of the main advantages of a collaborative robot is that it can operate in the same environment where the operators is without fences. However, this needs to be done safely in a shared workspace. The layout analysis is fundamental to understanding the space needed for the introduction of the collaborative robot. This analysis is a complementary activity of the process mapping although, in this case, the main focus is the workplace, not the process.

It is important to deeply investigate the workflow of the parts, if there are buffers along the process and where they are positioned, how fast the parts move along the process, if a priority exists between parts of the same family. Also in this case, the resources have to be taken into consideration and this includes not only machines, tools and equipment, but also operators.

Another important element is the flow of information that happens between the cell and other parts of the factory, as well as within the cell. What information comes into/out of the cell, how they are transmitted and how do they affect the task are an example of possible details that can be used to represent the work cell. In this sense, it can be useful to create a table with the information, showing where it comes from, where it goes, what form it takes, and what it impacts.

Guiding questions

How much space is dedicated to the work cell? Is there enough space for a collaborative robot to perform a task?

Are there any buffers along the process?

How many parts constitute a batch?

Is the work cell only used for the process under analysis?

Where are positioned the tools necessary for the processing of the part?

Are there any obstacles to the installation of a cobot?

What information needs to be passed between the operator and the machines?

How many workers are involved in the process and act in the work cell?

Identify critical Key Performance Indicators (KPIs)

This step is fundamental to identifying the indicators that allow measuring the transition from a manual process to an automatic/collaborative one. They are necessary to understand the existent performance and the impact of the new solution. KPIs can be of different nature and, in the literature, it is possible to find several ways to classify and categorise them. Tightening the circle to what is the purpose of the deployment of collaborative robotics, the most important types of KPIs are operational and human-related. While human-related indicators are intended to help the company in understanding their employees' satisfaction and how the working conditions affect their wellbeing, operational indicators focus on monitoring and evaluating the day-to-day operations to help management identify which operational strategies are effective, and which actually inhibit the company. Some relevant KPIs can be process cycle time, number of non-conformities, the WIP level, worker wellbeing (e.g., through NASA index), work cell and task ergonomics (e.g., through RULA assessment). Usually, several KPIs are affected by the introduction of a cobot and it is difficult for the company to keep track of all of them. It is necessary to consider the following characteristics when identifying a KPI:

- **Relevance**: Is the KPI aligned with the goal of the process?
- **Descriptive:** Can the KPI be used to detail the process and provide a representation of its status?
- **Measurable:** Do we have in place what is necessary to measure the KPI? Is the KPI currently monitored? Is something similar monitored? What is the measure/unit of measure? Are the means of verification feasible?

After selecting the KPIs, the next step is to measure the AS-IS situation for all the indicators and then to define a target value.

Guiding questions

Which are the KPIs currently measured in the process?

Are there any other KPIs that can be relevant or affected by the deployment of a collaborative robot?

Are the desired KPIs easily measurable?

Are the desired KPIs able to provide a complete and valuable representation of the status of the process?

What are the values of the KPIs in the AS-IS situation?

What are the target values for the KPsl in the TO-BE situation?

Are there any other success criteria to be included?

The BRILLIANT experience

Detailed information has been collected by observing the selected processes, also interviewing operation, quality and production managers as well as the operators. This allowed to collect the characteristics, requirements and criticalities of each process. As of today, the tweezers are manufactured and assembled through manual operations with the aid of mechanical processing machinery. The method of manufacturing used is in batches of around 150 items. After each mechanical processing, the tweezers, contained in bins, are taken to the next working station manually. An operator is assigned to the sequence of tasks with a 100% degree of occupation. He takes over the execution of each mechanical processing and the subsequent check of the conformity of the parts (e.g., alignment of parts, glossiness, surface roughness). The operations, characterised by really short cycle times, are repetitive and alienating, forcing the operator to take numerous breaks to preserve his mental and, partially, physical health. This working condition inevitably affects the productivity and the quality of the output.

The whole process is represented in Figure 7**Error! Reference source not found.**, collecting different tasks. *For each one, task number, task name, duration, image and a brief description are provided. The process is also characterized by 4 buffers, represented in the figure as numbered triangles. The first four operations (0,1,2,3) are performed on the single plates while the remaining affects the whole tweezer. First of all, the single plates are cleaned (task 0) and shaped (task 1) to obtain a functional form for the required application. Before welding (task 4), two plates are picked (task 2) and inserted into a jig to ensure a proper vertical and horizontal alignment (task 3). The workpiece is then removed from the jig and stored in the bin (task 5). The tail of the tweezers is then grinded (task 6) with the aid of a belt*

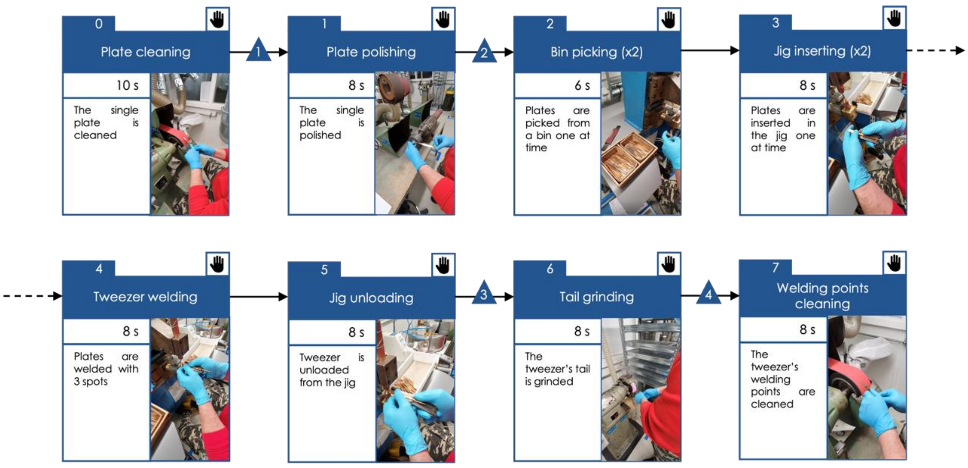


Figure 7 The BRILLIANT manual process

grinding machine. Finally, the operator takes care of cleaning the welding spots putting the tweezers in contact with a specific rotating tape (task 7).

The process has two main challenges that have to be considered during the collaborative work cell design and development:

- ***Plates alignment for precise welding**: the two plates have to be vertically and horizontally aligned to obtain in-quality welded workpieces. This alignment is currently achieved with a mechanical jig. This process is slow it requires high dexterity.*
- ***Welding point cleaning and polishing quality**: Ideal-Tek produces high-end tweezers, that must be compliant with strict quality requirements. These requirements are not only functional but also aesthetic. Cleaning and polishing have to be carried out to remove the welding residuals to obtain shiny surfaces minimising the amount of material removed.*

KPI	Goal	Means of measure	Target value
Number of accidents in the work cell	*Minimize health stress and risk to incur in accidents.*	*Worker must notify every time a near miss occurs.*	*Number of registered near-miss: -20%*
Job engagement	*Improve job satisfaction of workers thanks to the benefits obtained by adopting the BRILLIANT work cell.*	*By means of questionnaire evaluation.*	*Delta job satisfaction positive responses: +20%*
Variability of job	*Minimise the repetitive, high-risk and non-ergonomic tasks assigned to workers.*	*Direct observation of the tasks carried out by the operators during a shift.*	*Time dedicated to the same tasks: -40%*
Productivity	*Work cell productivity thanks to reduced variability of cycle time and increased product quality*	*By sample measurement of workstation output during the duration of the experiment*	*Units per day: +30%*
Number of scraps	*Scraps due to the repeatability of the cobot, higher control of the work cell and higher focus of the worker thanks to dynamic tasks allocation.*	*As an outcome of the quality control system during the duration of the project*	*Scraps produced: -20%*

3. WORK CELL DESIGN

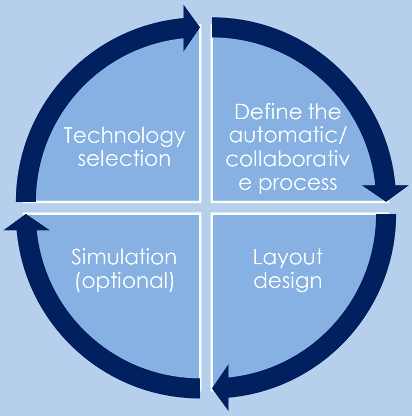
The work cell definition influences in a relevant way the performance of the collaborative work cell and, therefore, the return on investment. The design should consider many aspects, including the process constraints, human skills, the roles in the process, the cobot characteristics and the selected technologies. For this reason, it is suggested to follow a lean and recursive approach in order to properly address the high complexity and criticality of this stage.

The main goal of the work cell design process is the effective introduction of the collaborative robot in order to achieve the expected benefits and KPIs target values. Collectively, the modifications made to the process should dramatically increase productivity, savings, reconfigurability and human well-being in the workplace. The design process of a collaborative work cell needs as input the map and the layout of the manual process with a series of measurable indicators, including throughput time, cycle times, and resource saturation.

Define the automatic/collaborative process

This step requires to describe the sequence of operations and logic that characterises the automatic/collaborative process, considering what the cobot will do and how its tasks are influenced by and influence human activities. The definition has to carefully consider the following activities:

- To define tasks and operations and to formalise the process sequence. It is suggested to use flow charts, BPMN models and/or IDEF0 models;
- To assign the right tasks to the cobot and the right tasks to the humans;
- To define the main elements that have to be included in the work cell;
- To define part infeed and outfeed techniques;
- To define process sequence: how will the cobot execute the process;
- To define information flow and process logics.



Guiding questions

Which are the tasks/operations that will be maintained from the manual scenario?

Which are the new tasks/operations that will be introduced in the automatic/collaborative scenario?

How will the parts be presented to the robot? This decision relates to your choice of tooling and sensors. It is necessary to find the right balance of cost, flexibility, and complexity for your situation.

How will the parts be presented to the downstream process/station? Should the parts be presented directly to the downstream process/station or is it possible to add an intermediary step between the robotic cell and the original customer (such as some secondary inspection task)?

What information will need to be exchanged within the cell, and between the cell and other parts of the factory?

Which is the role of the operator?

Which are the interactions between the operator and the automation systems, including the robot?

Which are the decisions and logic that orchestrate the work cell?

Who is the orchestrator and decision-maker of the work cell?

Which are the possible unexpected events and failures of the work cell?

How unexpected events and failures can be addressed before or during operations?

Create the layout of the collaborative work cell

The work cell layout provides a detailed description of the work cell, showing how each station and elements composing it (equipment, parts, buffer, cobot, tools, etc.) are placed with respect to each other and with their direct environment in the work space. A sketch of the robotic cell layout has to be drafted and detailed taking into account:

- Process sequence;
- Spatial constraints (also for the setups and machines maintenance);
- Safety requirements;
- Part presentation.

The definition of the layout involves converting the production area to a cellular layout so that processing steps are conducted immediately adjacent to each other enabling the use of a cobot with a defined reach. The rearrangement of the elements composing the work cell should consider the following:

- Minimise non-value added time;
- Keep the items moving;
- Keep the process elements (machines, manual station etc.) logical and sequential (define the correct sequence/ division of work/line balance);
- The human operator must be able to reach all the relevant positions easily and his/her movements around the work cell have to be minimized;
- Make every single station ergonomic (size up the tasks, define the size range of the operators, and the relationship between one station to another);
- Optimize parts presentation at the point of use;
- Make documentation (use SOP);
- Minimize WIP;
- Minimize wasteful handling (minimize handling offline);
- Keep it open and flexible (scalable and encourage continuous improvement);
- Keep it simple (easy to maintain, easily reconfigured, low upfront cost);
- Ensure the cobot can reach all the relevant positions trying to economise on movements, minimising reach time and avoiding hyperextension;
- Make sure that the duration of the collaborative process (i.e., the one performed by the human operator and the robot together) is comparable to the duration of the current process (which is performed entirely by the human).

Guiding questions

Will the collaborative robot be installed in an existing or a new work cell?

Which are the shop floor areas available to place the collaborative robot?

Which utilities are needed to operate the collaborative robot?

What is the space occupied by the production machines?

How much space is needed for machines and the cobot cleaning, setup and maintenance activities?

Which are the potential motion constraints of the cobot?

What is the size of the batch to be handled? is it possible to reduce it?

Where are the buffers placed?

Which is the parts presentation?

Are the position of the machines and station proper to perform the task/activity sequence while minimizing wasteful handling?

Is the operator able to move freely and safely between in the work cell?

Create the robotic cell simulation model (optional)

The goal of this stage is to define the digital counterpart of the possible automatic/collaborative work cell in order to deeply analyse the tasks and operations sequence, cobot movements and to have a preliminary overview of the productivity performance. Pursuing this goal firstly involves the creation of a simulation model of the process under analysis. There are numerous tools on the market to develop the robotic cell like Webots, Microsoft Robotics Developer Studio, Roboguide, RoboDK, and RobotStudio.

Playing with a simulation model enables the following series of benefits:

- The manual process is not interrupted;
- Different layouts and workflows could be studied and evaluated also considering the technological and spatial constraints;
- It is safer and cheaper than the "real model";
- Different equipment and their parameters could be evaluated (e.g., type of the cobot, its reach or payload, etc.);
- Rapid and simple exploration of "what-If" scenarios can be used to find unexpected problems;
- Performance indicators could be easily computed and compared among others.

Guiding questions

Which are the insights that have to be obtained through the simulation? E.g., layout analysis, cycle time estimation, logic definition and evaluation, etc.

Which are the what-if scenarios to be simulated and compared?

Which is the level of detail that the simulation needs to achieve in order to provide relevant insights?

Technologies selection

After having defined the overall process and designed the work cell, specific decisions have to be taken on the technologies to be adopted. This selection could influence the process sequence and the design themselves. This is the reason why these steps are recursive. Therefore, during technology selection, possible modifications have to be considered. The technology selection should involve:

- Cobot
- Tooling and feeding systems
- Sensors
- Safety measures
- Software

The selection of the right cobot, the end-effector and all the equipment necessary to realise the automatic/collaborative work cell is always a difficult task, given the several solution available on the market. Figure 6 shows all the characteristics that should be carefully evaluated to select the proper cobot to minimise the purchase of wrong or even unnecessary solutions.

Figure 8 Collaborative robot characteristics

Guiding questions

Which brand and model of cobot has the right specifications for the process (reach, payload, speed, repeatability, compatibility with tools, etc.)?

What tooling, both on the cobot and elsewhere in the cell, is necessary for the process? You will also have to consider how these things will interface with your chosen cobot. Do not underestimate the effort (non-value-added effort!) needed to interface two machines that were not meant to work together.

Which control approaches are going to be used? E.g., closed loop control or logic-based programming using sensor data?

Which sensors will be used? E.g., limit switches, vision systems and force-torque sensors.

The BRILLIANT experience

The BRILLIANT team started the work cell design through a series of brainstorming moments in which the equipment needed, how to move parts, data architecture and some possible cell layouts have been discussed. After that, the simulation model of the cell using RoboDK has been developed and all ideas and concepts tested.

The production sequence is one-piece flow logic. Specifically, the nature of the first two activities has been maintained. The operator performs the polishing on the single parts and loads them into dedicated buffers. From this step onwards, the cobot takes charge of the subsequent activities. Specifically, the following operations are performed in sequence:

1. **Parts picking**: the cobot takes from the buffer the two pieces that constitute a tweezer one at a time;
2. **Jig inserting**: the cobot inserts the two pieces into a jig in the right direction;
3. **Tweezers picking**. the cobot takes the pieces in its gripper keeping them perfectly aligned and transports them to the welding station;
4. **Tweezer welding:** the two pieces, blocked in the cobot's gripper, are spot-welded together;
5. **Tail grinding**: the cobot brings the piece to the tail grinding machine where, respecting specific force and direction parameters, the welded tweezer is grinded in order to harmonise the shape making the geometry uniform.
6. **Cleaning of welding points**: the cobot with the piece in the jig goes to grind the welding points with one or more settable passes (yet in terms of path and applied force);

At the end of the sequence of tasks, the cobot unloads the processed tweezer and returns to the buffer to retrieve the new plates the operator has loaded in the meantime and restarts the sequence. **Error! Reference source not found.** shows the representation of the envisaged process.

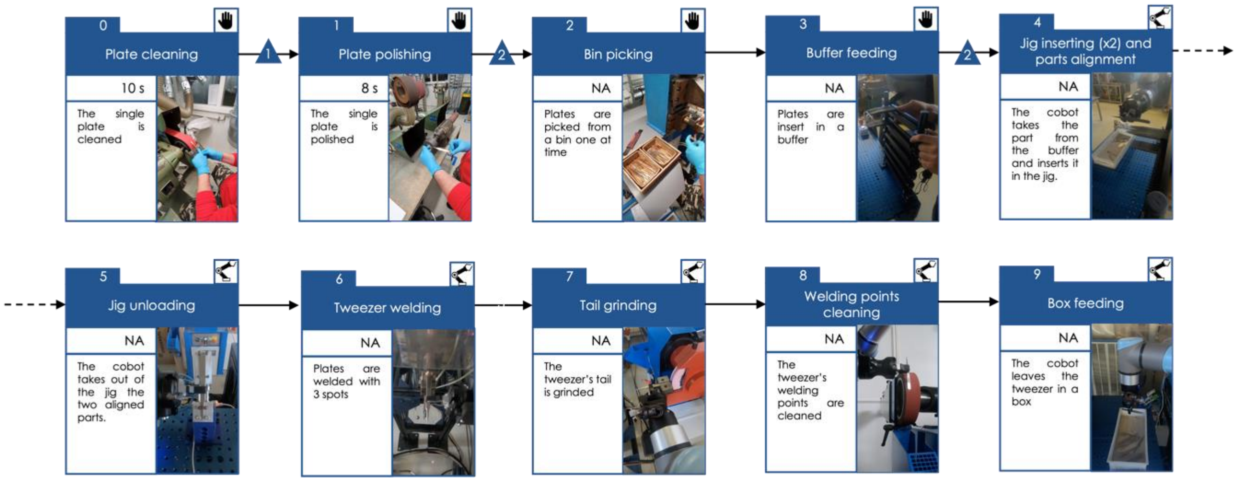


Figure 9 The BRILLIANT collaborative process

The sequence and the defined layout have been validated by simulating the movements of the cobot. A first version of the simulation setup designed using RoboDK[3] was created to analyse the cobot movements, and configurations and to understand if it was able to reach every point of the working space. Moreover, in this environment, it has been possible to program all the movements of the robot and run them, in order to check for collisions, reachability and required time. A screenshot of the simulated environment is provided in Figure 10, together with the laboratory workbench, where preliminary studies have been carried out.

Particular attention has been paid to the movements made by the cobot with the plates or the tweezers closed in its gripper. In fact, the motions are carried out in such a way that the operator could carry out safely his activities, without hurting the gripper. Similarly, machinery that generates risks for personnel, such as polishing machine or welding machine have been equipped with safety systems. All the necessary precautions taken for the safety of the operator will not affect the performance of the system. In this

[3] https://robodk.com/

respect, a set of performance indicators has been defined to track the performance of the system as a whole and to allow it to be improved in the near future.

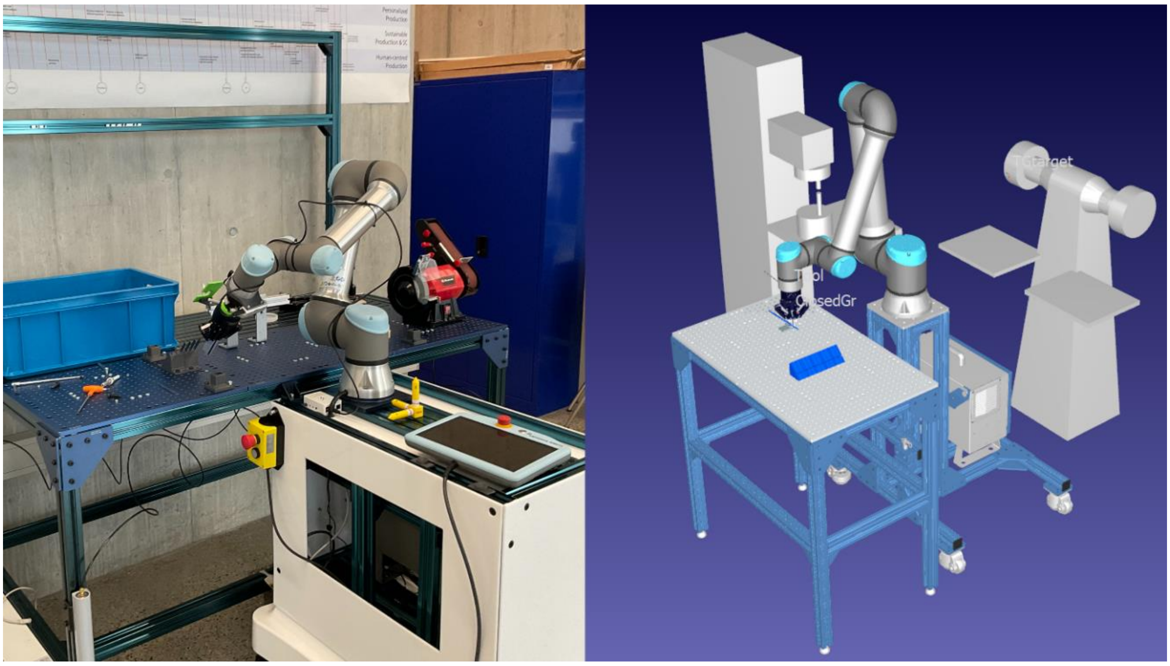


Figure 10 Laboratory environment and simulation of the process

4. PROGRAMMING THE SOLUTION

The programming process entails providing a cobot with the ability to perform a task that advances the system towards the expected goal. Usually, a robot programmer is involved in the off-line programming of a cobot. Here are a few hints identified by the team.

Get the most from free-drive mode

One of the main advantages of cobots is the use of the free drive mode, known also as hand guiding. It allows the collaborative robot to move under the guidance of the operator's hands and respond only to the operator's direct control input. The robot is powered and balances the weights and inertia of its body, the end-effector and even the picked workpiece it picks up with controlled torques and forces.

The use of a simple switch to activate free drive mode eases the movement of the cobot, giving the possibility to move the cobot with two hands, increasing precision and reducing the repositioning time.

Structure the program

Working with the main program and using sub-programs/scripts allows having the code cleaner. Moreover, these sub-programs/scrips can be called whenever necessary and tested singularly. Each sub-program/script has to be responsible for a specific independent task. The granularity depends on the application and on the re-usability requirements.

Rely on built-in features

Many cobots already include features that allow using complex control methods like force control or contact detection. For example, contact detection helps when it is hard to develop accurate movements that require knowing exactly where a part is without putting it in non-fixed positions (e.g., because the jig is bigger than the part, thus there is a margin error). Contact detection can be used to reduce the accuracy requirements. For example, the part does not need to be positioned in a very precise position, but the robot can assess its presence and position through contact detection.

Move complex logic outside the cobot

Complex applications require to coordinate different equipment and machines, to detect events and to take decisions based on these events. In this case, it is suggested to orchestrate everything through the cobot program and control can be complex and not easily manageable. In such complex scenarios, an external orchestrator in charge of the management of the work cell is suggested, in order to simplify the coordination and also to give the possibility for the operator to easily interact with it.

Use parameters

A single cobot can handle different types of products and also be used in different applications. This flexibility requires the ability to quickly set up and deploy the cobot. The use of parameters instead of fixed values allows the code to be more dynamic and to test different configurations in order to reach different results.

The BRILLIANT experience

The BRILLIANT logic structure has been structured on 4 levels: the **orchestrator program** that manages the work cell and coordinates the process; the cobot **main program** which is composed of **task sub-programs** (e.g., welding, polishing, etc.) which in turn are composed by the **operation sub-programs** (e.g., picking from the buffer, posing in the jig, etc.).

The BRILLIANT cobot is mounted on a carriage to be reassigned to different activities. The work cell has been divided in stations: buffers where the single blades of the tweezer are positioned; jig for the plates alignment; welding machine; grinding machine, polishing machine.

For each station, an "approach waypoint" has been defined together with a "process waypoint", which is the reference point for the cobot operation in the station. To increase the fast re-deployment of the cell, together with the possibility to scale the solution to new types of tweezer, a set of parameters for each station has been defined in order to deal with small reallocation errors (the BRILLIANT application requires a repeatability lower than 1mm) and with the different characteristics of the tweezers types. For example, the team used the number of polishing cycles and the force to be applied during polishing as parameters to deal with the different materials of the tweezers. Other parameters deal with the station re-allocation, modifying the "process waypoints". In this way, these points are redefined through a simple interface and setup procedure to reach the expected positions, even if the carriage location has been slightly changed.

The orchestrator coordinates the whole part programs to be executed, and checks the current status of the work cell including machines states, buffer levels, maintenance requirements, while providing an overview of the production order status.

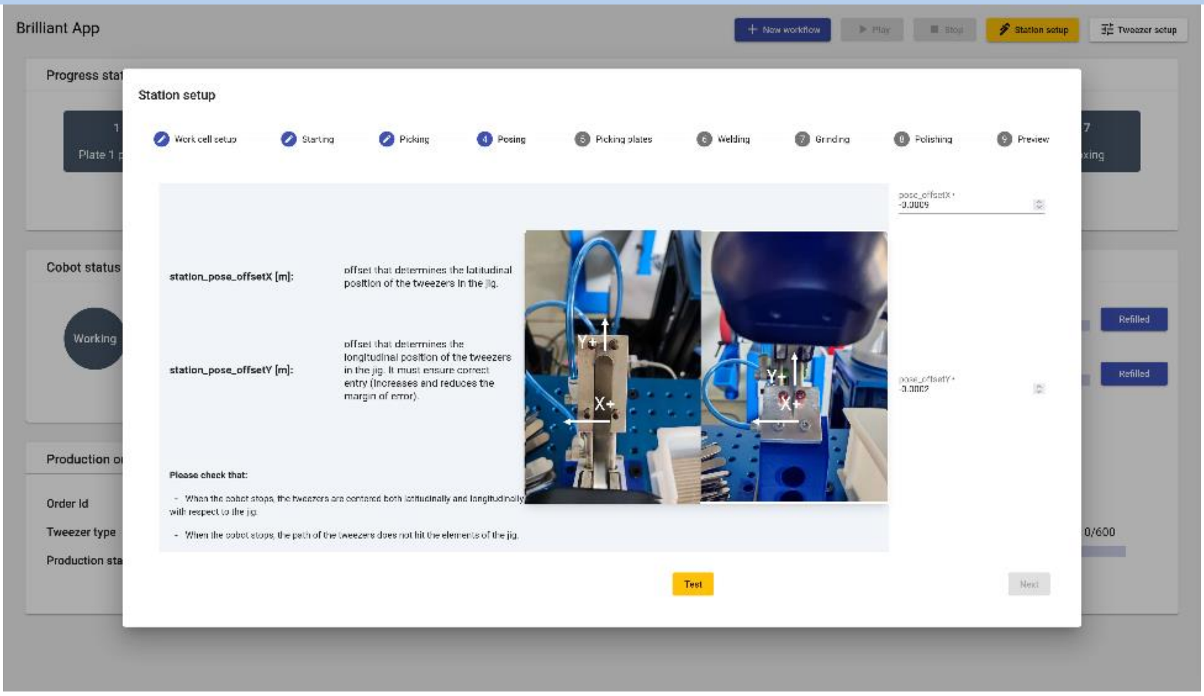


Figure 11 The BRILLIANT application

WHO WE ARE

The **Sustainable Production Systems Lab** (SPS) is a research institute belonging to the **University of Applied Science and Arts of Southern Switzerland** (**SUPSI**). The mission of the Institute is the innovation of production processes and business models in supporting companies in facing the challenges of digitalization under the economic, environmental and social aspects. The fulfilment of the mission is achieved through the development and technology transfer activities with reference to the life cycle of products and industrial processes, in the fields of design, automation and management of production systems.

This research has been carried out in collaboration with:

Ideal-Tek SA (I-TEK) is a Swiss manufacturer and supplier of high-precision hand tools and instruments for different applications: medical, microscopy and laboratory, electronics and semiconductor, watchmaking and jewellery.

Holonix is a spin-off company of Politecnico di Milano that is involved as coordinators for industry 4.0 projects of small and medium-sized Italian manufacturing excellence that aim at adopting the new model focused on the availability of Big Data and collaboration between humans and Artificial Intelligence (AI).

Do you want to develop a project or a feasibility study on a collaborative robotics application?

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