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A NEW TASK ALLOCATION METHOD FOR MOBILE COLLABORATIVE ROBOTS IN AUTOMOTIVE FINAL ASSEMBLY

Supervisors	**Candidate**
Prof. Maria Pia Cavatorta	Edoardo Branda
Prof. Ali Ahamad Malik	

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This Master Thesis is the final chapter of a journey that has not only been mine but has been shared with several outstanding people I met along the way and that contributed significantly to accomplish everything I have done.

In these few lines I would like to thank my parents, Francesca and Massimo and my whole family, for the continuous and loving support I always received, without which I would probably not be here. I would also like to thank an amazing team, Alberto, Giorgio, and Riccardo, I was more than lucky to work with through classes and project years and that made this year of education lighter and more passionate thank a nearly always healthy competition.

The years at the Politecnico have been the most challenging ones, and yet the most meaningful of my life, and for this reason I want to say to my whole family, to all the new and old friends that supported me and to the amazing professors that passionately shared their knowledge every day for five years, thank you.

Abstract

A NEW TASK ALLOCATION METHOD FOR MOBILE COLLABORATIVE ROBOTS IN AUTOMOTIVE FINAL ASSEMBLY

By:

Edoardo Branda

Automotive final assembly is a complex process involving tasks requiring a significant amount of flexibility, for these reasons it has been difficult to automate and is still performed largely manually.

Industry 4.0 concepts led to the deployment of collaborative robots, which don't require physical separation as conventional industrial robots and can thus work closely to workers, taking over dangerous and physically demanding tasks.

This research aim is proposing a new approach to Human-Robot task allocation and develop a systematic implementation framework to allow for an effective deployment of collaborative robot.

Primary objective shall be to identify the variables that mainly affects the productivity of a HR collaborative assembly.

The identified variables will be the main tool to propose a new task allocation method to assess the suitability of a task for collaborative automation.

The proposed method will be then tested and validated by implementing the process into a virtual simulation environment and final productivity, ergonomics and safety considerations will be derived.

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CHAPTER ONE

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The latest years witnessed a significant change in the demand coming from the market for the manufacturing industries.
The request for products with a shorter life cycle, more variants and with a higher mass customization is leading manufacturing companies to a need for a higher flexibility and a better responsiveness from one side, but with the constraint of keeping low production costs from the other side.

To face this problematic trend the idea of “Industry 4.0” and its related advanced concepts was born in Germany in 2011, relying on the idea of using digitalization and networks to automate processes and increase their flexibility.
It is possible, if a classification is wanted, to follow the definition of Klaus Schwab [1], who identified four main trends characterizing the fourth industrial revolution: unmanned vehicles, 3D printing, advanced robotics and new materials.

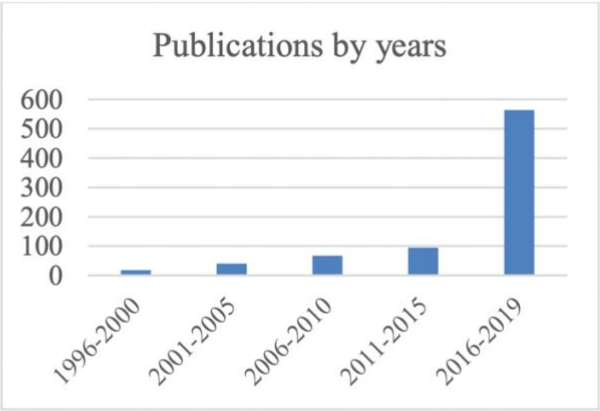
Extremely critical in terms of automation results to be the assembly process, which can be defined as “the sequential integration of parts and components into functional products” [2].

Due to the complex activities involved, which require a high level of dexterity and flexibility in order to be carried out, this part of the production has been difficult to automate and is still performed primarily manually in the vast majority of the cases.

However, a trend of increasing wages and aging of the workforce compels the industries to find new solutions to make the assembly of components more productive, without relying solely on the human workers.

A potential solution to this issue, born among the concepts of industry 4.0 and recently gaining more and more consensus [3], is the adoption of collaborative robots to aid the worker with complex and demanding assembly tasks.

Figure 1 Publications using "Collaborative Robot" or "Cobot" in the title or as a key word, Web of Science (Janaury 2020)



Source 1 "Collaborative Robots: Frontiers of Current Literature, by M. Knudsen and J. Kaivo-Oja, 2020, Journal of Intelligent Systems: Theory and Applications.

Collaborative robots are such robots that are designed to work along their human counterparts and share the same working space as coworkers [4]. They can thus be deployed in what is called a Human- Robot collaborative assembly cell, to aid the worker by taking over dangerous and physically demanding tasks.

The idea is then to join the best of the two worlds, realizing a hybrid collaboration which takes advantage of the best qualities of human and robot to carry out assembly activities in a productive and safe way.

Primary aim of this research will be thus to investigate which are the parameters that affects the productivity of a hybrid assembly cell and create a new task allocation model, intuitive and easy to apply to the majority of assembly scenarios, in order to evaluate task's suitability for automation and thus achieve the most proper job distribution between worker and robot.

1.2 Literature Review

1.2.1 Overview on collaborative robots

To effectively approach the deployment of collaborative robots (cobots) in a manufacturing environment, it is of crucial importance to be aware of the current state of the art the available solutions, and how authors and process designers have dealt with the problematics involved in the design of Human-Robot collaborative assembly.

To this aim Kruger et al [5] carried out an extensive review of the use of cobots for industrial applications, with a particular focus on assembly scenarios.
In their research they presented the state of the art of human-machine cooperation in assembly line, starting by identified which are the strengths of the former and of the latter.

Typically, an automated assembly line can provide advantages in terms of continuous operation with reduced breaks and fatigue and a higher productivity. However, drawbacks might arise concerning a restricted flexibility due to programming efforts in readapting the robot to a new process and to a limited ability to handle complex parts.

The authors also identified two main categories of hybrid assembly systems [5]:

- Workplace-sharing system: in this scenario human and robot are both working in the same workspace, either the worker is performing an assembly task and the robot is performing and handling one or the other way round.
- Workplace and time-sharing system: in this scenario robot and human are also allowed to jointly perform either an assembly task or a handling task. To allow for this degree of collaboration the robot must be allowed to interact physically with the worker.

Implementing a collaborative robot means facing several challenges, the most crucial one being to ensure worker's safety; granting an effective human-machine cooperation and that the two resources are aware of their respective location at every instant.

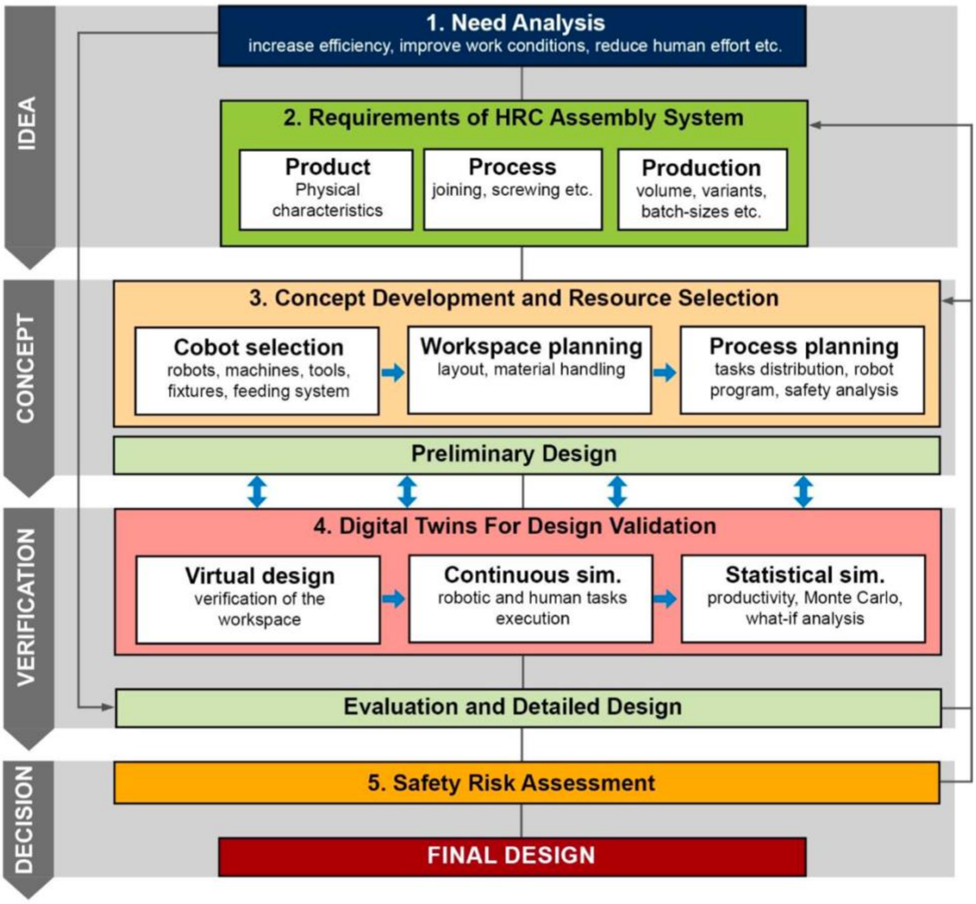
However, although being a parameter of utmost importance, other equally complex issues shall be addressed to justify the deployment of a collaborative robot.

To this aim, the next three sub-chapters will deepen the main challenges that can be encountered while designing Human-Robot Collaboration (HRC), respectively: the implementation procedure to be followed to deploy a cobot, how to distribute tasks between Human and Robot, HR communication means and technologies and finally safety requirements and available solutions.

1.2.2 Implementation Frameworks for Collaborative Robots

To redesign a production process, it is necessary in the first place to study the process demand and requirements, which can be translated into examining the boundary conditions, limitations, standards and laws to comply to and so on [7].

Figure 2 Conceptual Framework to Design an HRC Assembly Cell



Source 2: Source 1 : From "A Digital Twin Integrated Framework to Deploy Collaborative Robots: Case of an Industrial Assembly Cell"; by A. Malik, T. Masood, A. Brem. Reprinted with permission

To allow for a better and easier understanding about which steps have to be dealt with during the design of a flexible assembly system, a possible approach is the so called| “factories as products” .

Starting from this idea, in [6] an integrated systematic design for changeable manufacturing system is derived from a comparative analysis between the concepts of ‘product design’ and ‘manufacturing system design’.
According to this approach, just like a product the starting point shall be an analysis of the requirements of the process in terms cost, time, quality, environmental impact and so on.

Thus, the theory of “factories are products” can be applied to ease the task of the design and validation of a flexible manufacturing systems.

In a similar way, Malik and Bilberg [7] applied this new concept for the development of a systematic implementation framework for HR collaborative assembly cells.

According to their approach, the authors have derived a three-phases framework to allow for the adoption of a collaborative robot, namely:

- Idea & Concept Phase: which involves analyzing the business needs (production data, potential saving, expected quality) and the production process (process sequence, properties of the parts), to identify the requirements for a hybrid assembly system.
- Exploration Phase: in this phase the process and business needs are translated into requirements for the functional elements (robot, gripper, operator) and provisional design layout (material handling, feeding system)

- Decision Phase: this step involves the conclusion of a provisional design, the development of a virtual prototype and, through its validation, the achievement of a final design

An extremely important and yet one of the most challenging problems of the decision process just presented is the choice of which technological resources shall be integrated in the new assembly cell.

The selection of the industrial robot and its end-effector for a specific industrial application has become more and more complicated due to the increase in complexity, advanced features and sensors that are continuously incorporated into the robot.

The goal is thus to find the best compromise between the process needs from one side and the available technological solution from the other one.

To this aim Chetterjee et al. [8] developed a decision maker that could identify and select the best suited robot for an industrial application, able to reach the desired output with the minimum cost and the required application ability.
The approach used by the authors is to compare the relative performance of the robots by means of two Multi Criteria Decision Making Methods (MCDM).

The first one, called VIKOR method, is developed to solve MCDM problems with conflicting criteria with different units; its aim is to offer a ranking of alternatives as output, assuming that a compromise can be acceptable for a conflicting solution.

The second approach is an outranking method called Elimination and Et Choice Translating Reality (ELECTRE) based on the intention to improve the efficiency without compromising the outcome.
Objective of this method is to find the alternatives that dominate the other alternatives

and cannot be dominated by any other alternative, and finally find the best one by introducing the knowledge of the relative weights of all the criteria affecting the decision-making process.

The chosen end effector ultimately defines the capability of the robot to effectively be able to handle a determined set of classes of object or carry out a specific kind of task.

The latest years witnessed the development of several different grippers which can be similar to each other as well as be extremely different according to their application goal.

Some of the most common application for robot’s end effectors are:

- Manipulation: e.g. Grippers, Hands, Electromagnets, Suction cups
- Material extraction: Drilling, Milling, cutting tools
- Joining: Welding, Gluing, Fastening

The choice of the gripper can be dealt with using the same approach as it can be done for the robot, the final decision shall result from a comparative analysis between the process requirements, the physical characteristics of the parts to be handled and the tasks to be performed.

1.2.3 Human – Robot Task Allocation

As previously mentioned, the main goal of a collaborative assembly cell is joining the best of the worlds, i.e. the best qualities of the robot compared to the worker and the unique skills of the worker, following the concept of Humans Are Better At – Machines Are Better At (HABA-MABA). [9]

The decision upon whether to assign a task to the robot or not is depending on several factors, mostly concerning safety of the worker, collaboration mode embedded in the cell and the actual capability of the robot to carry out a task according to its technical specifications.

Because of the variety of constraint that must be considered when performing this kind of job distribution, as well as the different parameters that can be improved (or worsened), together with the fact the cobots are a relatively new field of research, it is difficult to define a general systematic procedure to carry out the task allocation.

The state of the art of collaborative automation is not yet able to offer a task automation mapping procedure able to consider all the parameters of major importance in a manufacturing environment (productivity, safety, ergonomics ecc) that can be applied to a broad range of industrial scenarios.

It is rather more common to find approaches tailored on the specific case study, whose decision of which variables to evaluate when assigning the task is up the designer.

The production variables that play a primary role when evaluating the possibility of automation can be several, among them the most considered being the complexity of the task in terms of technical and handling requirements [10] [11][12], physical workload on the worker [12] [13][28], cost of production and investment [12] [14] [15] and finally cycle time [12] [15] [16][28].

To evaluate the above-mentioned production variables in an automation perspective, different mathematical approaches can be considered: [12] followed a three steps procedure starting from the development of a set of four indicators (part weight, displacement, accuracy and dexterity requirements) to associate to each task, then a classifier assign the tasks according to the indicators values for each task and finally a last assignment is performed considering task duration and precedence.

In [11] a genetic algorithm for HR task distribution is presented, whose aim is to obtain a computational process evolving to optimized assembly line configuration where both human and robots can be present. Thus, the elements of a genetic algorithm (chromosome, fitness function and genetic operators) have been tailored in order to create different combinations alongside the assembly line and defined in the following way:

- A task-sub chromosome, including a list of assembly tasks in order of execution so that precedence is respected. Therefore, the length of the chromosome, i.e. the number of the gens, is equal to the number of tasks.
- A human-robot sub-chromosome, containing a sequence of workers and robots assigned to perform each task.

The creation of the workstation is made, for each chromosome, according to the execution time of each assembly task, which must be preliminary classified according to its suitability of performing it by a human or by a robot.

- Fitness function: for each chromosome, is evaluated according to weighted sum:

$$F = \left(\sum_{k=1}^{3} w_k * f_k\right) * p \tag{1.1}$$

The three objectives are f_1, f_2, f_3.

- Minimization of the cost (f_1): where N = considers the number of workstations, the hourly labor cost, the number of equipment units and their costs.
- Minimization of skilled workers (f_2): is to group complex operations requiring skilled workers in a limited number of workstations.
- Minimization of the load variance (f_3): based on their energy expenditure (modeled using the modelization of Garg) and thus on their capabilities and level of collaboration with robots.

However, also more holistic approaches have been used to achieve a task HR distribution, in [10] the authors developed a system of describing indicators associated to three variables of interest (part properties, parts presentation, joining process) assigning scores according variables descriptions matching common manufacturing scenarios.By associating the task description to the one to be assigned, the score are summed up and averaged to achieve a final value suggesting the resource that should take care of the specific task. A final distribution is then performed considering task precedence and duration and finally the proposed method is applied to a manufacturing use case for a final validation.

A different methodology is proposed by Heydaryan et al [17] in their attempt to redesign the manual process for the assembly of an automotive disc brake into a human robot collaborative one. To perform the task distribution the authors did not propose any structured procedure, conversely they rely on the opinions of robotics and automotive manufacturing experts to make a decision upon which jobs should be automated and which not. As a first step the authors prove the conveniency to adopt a human-robot system over a manual one by analyzing four production variables of interest: Productivity, Quality, Human Fatigue and Safety, identifying the last one as the one having the larger weight in terms of importance.

As a next step the authors analyzed the tasks involved in the process using the Hierarchical Task Analysis (HTA), by mean of which tasks are defined as goals and sub-goals that must be completed in order to reach a final goal.

This well-established methodology proves extremely useful for the personnel participating in the study to determine the collaborative task between the robot and the worker. By later implementing the new redesigned hybrid process into a virtual simulation environment they eventually proved that even though the cycle time slightly increases, significant benefits can be achieved in terms of ergonomic improvement for the human worker.

The examples just shortly described, although being few of the ones available, are already able to provide a first understanding regarding how different the methodologies to approach the problem of HR task allocation can be and how the considered variables can be completely different depending on the manufacturing scenario and the aim of the study.

However, one thing that can be found common to most of the studies, if not to all of them, is that a strong element of subjectivity is still involved in the decision-making process.

Even the structured methods embedding tools such as computer classifiers or genetic algorithms to perform the job distribution start from a task analysis and evaluation which is strongly dependent on the subjectivity of the person carrying out the study.

It is in fact not possible, at least as far as the knowledge of the author of this study is concerned, to provide an objective evaluation of the task, which can be also comprehensive of all the parameters that play a role in the automation of a manufacturing process.

Obviously, some variables can be evaluated in an objective way, for instance the capability of a robot to pick up a component by comparing part's weight and dimensions to the technical specifications of the robot, but some others important characteristics, such as the dexterity required from a task, can only be evaluated according to the opinion of the designer.

1.2.4 Safety in a Human-Robot collaborative environnement

As previously stated, developing a new industrial scenario featuring human workers and robots working together is complex process involving several different crucial steps in order to be not only feasible but also effective.

A safe close collaboration between the human and the robot is to be achieved by performing a deep hazard analysis and risk assessment brought by the involvement of robotic partner, and eliminate or mitigate them through a combination of sensors, safeguards and communication devices integrated in the work cell.

However, the real challenge of this task is to achieve a safe and productive working environment at the same time: if on one hand it is of primary importance not to endanger the worker at any time, on the other hand the designed cell shall ensure that the safety protocols embedded do not compromise the benefits brought by the deployment of the robot. In fact, if down times due to robot stops because of the worker entering a danger zone get too frequent, or simply the safety protocols are not efficiently designed, it is likely that the cycle time is extended to the point that it is not convenient anymore to deploy a cobot.

If on one hand the sharp increase of interest during the last years in collaborative robots led to a significant development of advanced HR communication system and new technologies for sensors and vision systems, on the other hand international standards and regulations are struggling to keep up with the technological advancement, resulting in non-necessary limitations that make the use of collaborative robots not feasible.

Until recently, the only point of reference for industrial robotics designers were the ISO 10218-1:2011 (Robots) & ISO 10218-2:2011(Robot Systems and Integration) [19] [20], both describing generic guidelines needed to achieve potentially hazard-free collaborative working environment by assuring safe human-robot interactions.

The first part of the ISO 10218 is deputed to provide a general insight and knowledge of industrial robots, specifying safety requirements, protective measures and information needed for the use of robots.
It also describe some basic hazards associated to the robots and provide basic requirements to eliminate or mitigate the risks deriving by those hazards.

However, it should be noted that these guidelines only address industrial robots, and thus result to be extremely general and restrictive if they have to be applied to collaborative robots. Moreover, it should be considered that this standard does not address the robot as a complete machine, and thus hazards and features systems-related are not taken into account.

The second part of the ISO 10218 goes a bit further, focusing on the description of the hazards and the safety requirements related to industrial robots and industrial robot systems, including also:

- Design, installation and maintenance of the system
- Information needed for design, installation and operation
- Component devices of the system

However, this standard too still addresses only industrial robots, not providing any specific guidelines when a close collaboration and physical interactions between the worker and the robot are needed.

To partially solve this lack of guidelines, in 2016 the ISO 15066 [21] was published: although being actually a set of "best practices" and not a standard, its scope is to extend the guidelines of ISO 10218 by specifying the safety requirements specifically for collaborative robots systems and the work environment.
One of the most significant innovations brought by this standard is the description of how specifically a hazard identification and risk reduction analysis should be performed by describing the possible human-robot collaborative operations and identifying the requirements for each of them.

The ISO 15066 identifies four methods of collaborative operations:

- Safety Rated Monitored Stop (SRS): This feature is used to stop the robot motion before an operator enters the collaborative workspace to complete a task.

- Hand Guiding (HG): According to this method an operator uses a hand-operated device to transmit motion commands to the robot system.
- Speed and Separation Monitoring (SSM): In this mode human and robot may move concurrently in the collaborative workspace. Risk reduction is achieved by always maintaining at least the protective separation distance between operator and robot.
- Power and Force Limiting: In this method physical contact between the operator and the robot is possible, either intentionally or unintentionally. Risk reduction is achieved either through safe means in the robot or through safety related control systems.

Furthermore, the ISO 15066 aims at describing how the parameters playing a role in a HR collaboration risk assessment and reduction (e.g. robot's speed, force, pressure etc…) should be evaluated by providing evaluation procedures and specific mathematical relationships. Finally, following a pain tolerance study, the standards defines the biomechanical limits for 48 body regions in terms of force, pressure and energy transfer, this in order to provide the designer with reference values for the risk evaluations.

Nevertheless, even considering the guidelines provided by the ISO 15066, significant uncertainties remain around its integration [22] [23] in HR systems and its effectiveness [22] [24] remain.

Even with the premises and guidelines specified by [19][20][21], from studies in the literature it remains extremely unclear how designers and integrators should deploy safeguards to achieve the requested risk reduction or, most importantly, which systematic sequence of actions a designer should follow for the safety validation or which methods he/she should use to perform the risk assessment.

This is why, starting from this premises, Chemweno et al. [22] carried out an extensive review of the safety requirements for a Human-robot collaborative workstation, exploring the gaps between the standards and the real applications and showing how a poor hazard analysis can be detrimental for the safety of the worker and the productivity of the cell. As a way to partially solve this issue, the authors presented a systematic framework for orienting the design safeguards in compliancy to the normative standards, to analyze the outcomes of the hazard analysis and perform a risk assessment.

1.2.5 Research questions and objectives

From the literature survey of the state of the arts for collaborative robots just presented, it appears evident how the problem of HRC design is still a newborn research topic which shows significant room for improvement.

An extensive analysis of the existing literature enlightened two major weaknesses in the human-robot task allocation methods proposed so far.

The first weakness is represented by a substantial limited number of decision variables considered when designing the task allocation decision algorithm. As already mentioned, some of the most considered decision criteria are the physical properties of the part/tool to be manipulated, or the improvement in the operations cycle times.

However, when deploying a collaborative robot several new design aspects need to be considered and studied. As a matter of fact, a communication system between human and robot needs to be designed and the requirements for the enabling devices shall be defined; a hazard analysis and risk assessment related to the presence of the cobot must be carried out, with a consequent deployment of safeguards and safety protocols.

These aspects of HR collaboration play a key role in the definition of the operations cycle times and on the actual feasibility for automation. In fact, if automating a specific task may appear beneficial when comparing the execution times, it might result counter-productive after all the necessary safeguards and communication protocols have been designed and embedded in the process.

However, these issues are hardly considered when designing a new logic for HR task distribution, which usually relies on the subjective evaluation of one or two decision parameters with a limited analysis scope.

Hence, this study takes on the research question of which are the aspects of a HR collaboration the play a primary role in defining the feasibility and the actual effectivness coming from the deployment of a collaborative robot.

The second research question that will be dealt with in this study will be whether it is possible to design a new method for HRC task assignment that, after identifying the design variables, could take them into account at the same time to provide an effective evaluation of HR task, intuitive and easy to be implemented.

As previously hinted, most of the HRC task allocation methods available in the literature present a second major weakness, i.e. the current state of the art of collaborative automation still suffers from a significant component of subjectivity when it comes to assess the possibility to automate a task.

Due to the lack of standards and the fact that collaborative automation is a relatively new-born science, in the vast majority of research studies the decision variables associated to the tasks to be carried out are scored by the authors, who relie either on their own experience or on opinions from automation experts.

One of the objectives of this study will be thus the attempt to propose a new HRC task allocation method able to assess the suitability for automation in a more objective way, which shall not rely solely on the experience of the designer and can thus be applied to a broader range of different scenarios.

To further increase the objectivity and the robustness of the proposed approach, the fourth and last research question will be whether it is possible to test the effectiveness of the new task allocation method by implementing it in a virtual simulation environment, one of the leading concepts of the industry 4.0 philosophy.

Finally, a significant innovation brought by the following research is given by the attempt to propose a new approach for human-robot task allocation, more exhaustive and objective, while assuming the deployment of autonomous mobile collaborative robot. In the collaborative manufacturing landscape, this has so far been attempted only in laboratory scenarios, mainly with the goal of studying the dynamics of the interaction between a worker and his/her robotic assistant [25][26].

CHAPTER TWO

METHODOLOGY

2.1 Scope of the work

The scope of this research is the development of a new systematic task allocation method, with the aim to evaluate the requirements of the activities to be carried out in an objective way and consequently perform an effective task distribution between the worker and the robot. Currently, systematic frameworks able to analyze and assess the feasibility for robotic collaboration for product assembly are not available yet.

Through the study of the literature and of a real industrial use case and its implementation in Tecnomatix Proces Simulate^{TM} virtual simulation environment, the goal is to identify which are the variables impacting the actual feasibility for automation and the productivity of the possible HR collaborative assembly cell.

The developed method aims at providing an easy implementable mathematical model to evaluate the suitability for automation of assembly task, in order to provide a systematic framework to be used in the early stages of design for the implementation of autonomous collaborative robots. A schematic of the methodology followed is presented in Figure 3; the starting point of the research is a set of the CAD files of the parts to be assembled, a recording of the assembly process and a schematic breakdown of tasks and sub-tasks, provided by STELLANTIS SPA.

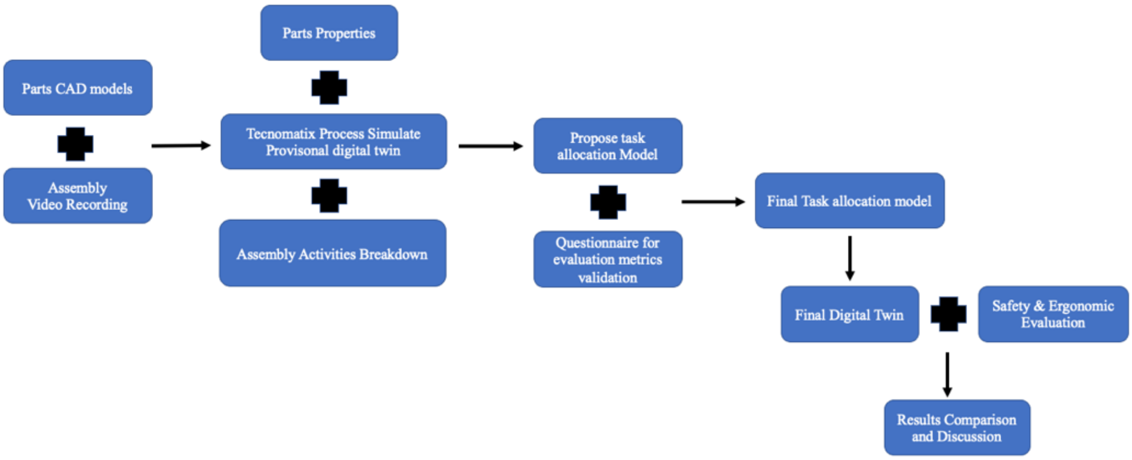


Figure 3 Methodology of the research

2.2 Analysis setup

This research is developed with the purpose of finding a new method that could objectively evaluate and assign tasks to human and robot considering their respective strengths and weaknesses when it comes to assembly operations.

In comparison to most of the existing studies investigating HRC, one of the strengths of this research is the possibility to test the robustness of the proposed task allocation method by means of a real case assembly scenario, directly provided by the car manufacturer STELLANTIS SPA.

2.2.1 Input data analysis

As previously hinted, the data used throughout this research study have been provided by the automotive company STELLANTIS SPA; the given data are mainly of three types: video recordings of the manual assemblies as they are currently performed, a listing of the assembly tasks to be carried out and finally data concerning components and tools to be handled (CAD files and part material properties).

The available initial data can thus be regarded as of mixed type, i.e. qualitative data concerning the task descriptions and quantitative data regarding parts physical properties, forces required to complete the assemblies and operations’ cycle times.

The case study used to test the proposed task allocation method involves the final assembly of the front door of a SUV. The assembly process is subdivided into three different assembly stations, which carry out tasks in parallel with a working cycle time of approximately 5 minutes each.

The tasks were recorded, as they are currently performed, by means of the camera of a smartphone, while the process was taking place in a STELLANTIS laboratory research environment simulating the real manufacturing scenario. (Fig.4-5)

2.2.2 Assembly components and task properties

The parts to be handled are extremely different one from the other in terms of shape, sizes, and materials property, which represent a major challenge for the robot handling given the flexibility that is required to the manipulator to effectively grasp and handle all the parts. Bulky and flexible components are involved (e.g. Door glass seal, waterstrip seal) as well as fragile parts (e.g. rearview mirror) or light, rigid and thus easy-handled components (e.g. anterior and posterior vertical coverages)

To allow for a better understanding of the activities to be carried out and their requirements, a breakdown analysis of the production process has been carried out.

Figure 4 Screwing Operation - Example

Figure 5 Positioning Operation - Example

Several approaches currently available in the existing literature can be used to identify and analyze all the activities and the tasks and sub-tasks involved; among them one of the most well estabilished is the hierarchical task analysis (HTA)[27]. The HTA is scientific method to identify human tasks with a core ergonomic approach, it is based on goal-directed behaviour comprising a sub-goal hierarchy linked by plans. The plans determine the conditions under which any sub-goal is triggered. As extensively explained in [27], the HTA is a goal-based analysis of a system with 30 years of history and a wide range of applications; it can be used to decribe both human and non-human tasks performed by the system, examples of applications of the HTA to a HR collaborative scenario con be found in [17][28].

Table 1 Assembly Components Properties – Workstation 1

Component Name	Weight [Kg]	Longest Diagonal [mm]	Flexibility Degree	Fragile Surfaces
Front glass door	0,6	653	low	yes
Posterior Vertical Coverage	0,3	454	Low-medium	No
Front Doorseal	0,3	1060	high	No
Anterior Vertical Coverage	0,2	476	medium	No
Waterstrip	0,2	974	high	No
Rearview Mirror	1,1	138	low	Yes

The procedure followed to describe the tasks and sub-tasks involved in the process can be summarized in the three key steps described in [27]:

- At the highest level it has been chosen to consider a task as consisting of an operation defined in terms of its goals.
- The operation can be broken down into sub-operations, each defiend by a sub-goal measured in real terms by its contribution to overall system's output goal and measurable in terms of performance, standards and quality.

- The relationship between operations and sub-operations is one of inclusion; it is a hierarchical relationship and the sub-goals have to be attained in a sequence.

To report the results of the HTA the tabular format is used, as it permits more details about how the activity is carried out and possible additional information. The results of the analysis is reported in Table 2.

As a result of the analysis, six super-operations were identified and broken down in their sub-tasks. In order not to excessively complicate the analysis the task have been broken down up to the second sub-level.

The usefulness of this analysis is to identify the assembly tasks involved according to their goals and their ergonomic characteristichs, thus allowing to acquire a first understanding of the requirements for the technological resources (Chapeter 3) that shall be deployed and for which activities the deployment of a collaborative robot could be beneficial.

2.3 Research Study Development

Primary research aim is to develop a new task allocation method that could effectively give an answer to the research questions presented in the introduction to this study (sub-chapter 1.2.5). Throughout this study the approach chosen to fulfill the above-mentioned goals has been a so called mixed-type research method, i.e. both quantitative and qualitative. The first step has been identifying the variables that primarily affect the cell productivity and the actual possibility to automate a specific task

Table 2 HTA of the manual assembly of the front door

Super Ordinates	Task Components, Operations and Plans	Notes
0	Final Assembly of the front door on the first assembly station ; Plan 0. Do 1,2,3,4,5,6 then exit 1. Assemble the front glass door on the assembly cart 2. Assemble the posterior vertical coverageon the assembly cart 3. Assemble the glass door seal on the assembly cart 4. Assemble anterior vertical coverageon the assembly cart 5. Assemble waterstrip on the assembly cart 6. Assemble the rearview mirrror on the assembly cart	
1	Assemble the front glass door on the assembly cart; Plan 1., Do 1.1,1.2, then 1.3,1.4 and 1.5 two times, then and exit 1.1 Pick Front glass door from the cart 1.2 Position front glass door on the cart 1.3 Push component against anterior door side 1.4 Pick scredriver from shelf 1.5 Take one M12 screw from pouch 1.6 Position the screw on tool tip 1.7 Fix front glass door by screwing 1.8 Place screwdriver on shelf	
2	Assemble posterior vertical coverage on door frame; Plan 2. Do 2,1, 2.2, 2.3, then 2.4, 2.5 and 2.6 three times, then 2.7 and exit 2.1 Pick coverage from cart 2.2 Position coverage on the door frame 2.3 Pick screwdriver from shelf 2.4 Take one M12 screw from pouch 2.5 Position the screw on tool tip 2.6 Fix coverage by screwing 2.7 Place screwdriver on shelf	

Super Ordinates	Task Components, Operations and Plans	Notes
3	Assemble left front doorwindow seal on door frame; Plan 3. Do 3.1, 3.2, 3.3, 3.4, 3.5 and exit, if 3.5 not correct then again 3.4>3.5 3.1 Pick seal from assembly cart 3.2 Position seal on door frame 3.3 Insert seal in the outer part of the door 3.4 Insert seal in the inner part of the door 3.5 Visually check the insertion	
3.1	Insert seal in the outer part of the door; Plan 3.1. Do 3.1.1, 3.1.2, 3.1.3 and then exit 3.1.1 Start inserting manually from the belt side (Rif1) 3.1.2 Continue manually the insertion to the other side 3.1.3 Insert the component from the rear area of the B pillar door by coupling it with the sheet metal flap	
3.2	Insert seal in the inner part of the door; Plan 3.2. Do 3.2.1, 3.2.2, 3.2.3 and then exit 3.2.1 Go to the other side of the door 3.2.2 Apply the component placing it inside the duct 3.2.3 Arrange it up to the B pillar using manual pressure	
4	Assemble anterior vertical coverage; Plan 4. Do 4.1, 4.2, 4.3, 4.4, 4.5 and exit, if 4.5 not corret then again 4.4 >4.5 4.1 Go to outer part of door 4.2 Pick vertical coverage from assembly cart 4.3 Position vertical coverage on door frame 4.4 Apply force to insert joints in their slots 4.5 Visually check the coverage insertion	
5	Assemble weatherstrip front door belt end; Plan 5. Do 5.1, 5.2, 5.3, 5.4, 5.5 and then exit, if 5.5 not correct then again 5.4 > 5.5 5.1 Pick belt from assembly cart 5.2 Insert the belt in on the sliding seat starting from the front door area 5.3 Manually insert the gasket into the groove	

Super Ordinates	Task Components, Operations and Plans	Notes
	5.4 Using manual pressure slide the gasket up to the B pillar 5.5 Check the correct alignment	
6	Assemble front left rearview mirror. Plan 6. Do 6.1, 6.2 6.3, 6.4 and then exit 6.1Pick mirror from assembly cart 6.2 Insert connector 6.3 Take the wire and insert its connector 6.4 Manually couple the mirror into the slot below	

This goal has been reached through an extensive literature survey, the analysis of the real assembly scenario provided by STELLANTIS (task/parts properties and requirements) and finally its implementation into a virtual simulation environment.

Once gathered the decision variables and the process describing criteria that shall be the structure of the new task allocation method, a questionnaire has been developed and refined in order to carry out in survey with experts with the aim to associate a score for automation to the identified criteria.

The primary goal of the questionnaire is to somewhat reduce the subjectivity of the logic that is usually used to distribute activities between human and worker. To further verify the validity of the questionnaire, a statistical analysis has been carried out on the results to prove the reliability of the questionnaire and optimize it.

In this research, a virtual simulation of the assembly cell process is performed to achieve two goals at two different levels. The main aim is to prove the validity of the proposed approach, by carrying out a simulation of the process according to the results given by the task allocation method. This allows to check its feasibility and effectiveness. On a second level, results concerning key performance indicators (KPI) regarding productivity and cycle time of the assembly cell can be extracted and compared to the ones of the process as it is currently designed, to verify if an actual overall improvement can be achieved through the approach proposed by this research.

Thus, the research method used throughout this study can be regarded as partially qualitative, as the identification of the variables through the analysis of the literature and the development of a questionnaire for a survey are both qualitative approaches.

On the other hand, implementing the process into a virtual simulation environment allows to extract quantitative data concerning the productivity of the cell, its ergonomic and the actual possibility to carry out the process as it has been designed through the results of the proposed task allocation method.

By means of this approach, the validity of the proposed method is verified and its robustness is tested by applying it to two different real case assembly scenario, which provide a reliable feedback on the applicability of the new task allocation method.

As a further achievement, the questionnaire developed has been tailored in such a way that it is possible to apply it to a broader range of manufacturing scenarios. It might eventually prove to be an efficient research tool; its flexibility allows to modify and update it as technologies and available solutions evolve over time. It can be thus used in the future as a means to update the pool of describing criteria and the associated scores, in order to allow for the new task allocation method to remain applicable despite changes in the manufacturing scenarios and in the technological limits of the resources available on the market.

CHAPTER THREE

DIGITAL TWIN DEVELOPMENT

In order to design and propose a new approach for the problem of HR task allocation, a preparatory study for the development of the new methodology has been set up. Aiming at identifying the decision variables for the proposed task classification approach and evaluate them in an objective way, the new logic has been implemented in a real industrial scenario provided by STELLANTIS through a virtual simulation, lately referred to as “Digital Twin”.

The primary difference between this kind of simulation and the pre-existing ones is that it does not prove to be useful only in the early stages of design, but having the possibility of being enriched with virtual representations of each component of the system, it makes it increasingly possible to simulate and verify its dynamic behavior as the system evolves over time. This newer approach to factory planning is thus called “digital twin”, that refers to its usefulness over the entire lifecycle of the simulated system. The information that a digital twin can provide already in the early stages of design are several, to this aim Fig.6 provides a first schematic understanding of the information that can be derived by means of this tool. The second purpose of the creation of a digital twin is the understanding of the parameters mostly affecting HR collaborative automation feasibility and productivity.

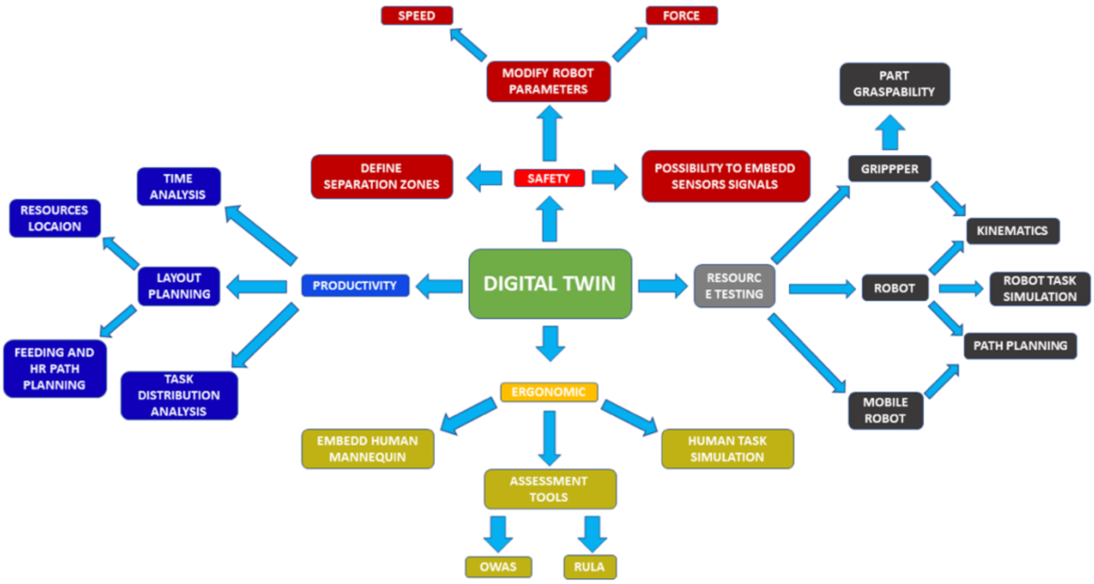


Figure 6 Digital Twin Schematics

This chapter will thus deal with the setup and implementation of the assembly process concerning the first assembly station. After showing how the environment in Tecnomatix Process Simulate has been developed, the next sub-section will present the implementation of an unstructured logic for HR task distribution, developing also its related collaborative virtual simulation. Finally, the results of the development of this holistic approach to the simulation will be presented and discussed.

3.1 Resources evaluation and selection

The breakdown of the assembly activities through the HTA, together with the analysis of the video recording of the manual process, have been the means to understand the basic requirements to the technological resources to carry out the collaborative tasks.

3.1.1 Autonomous Mobile Robot

One of the innovations of this research is attempt at a structured and effective implementation of a collaborative robot which, considered the frequent walking activities involved in the process, must be able also to navigate around the assembly station and to follow the worker for the collaboration to be efficient. The idea in this case is to adopt an autonomous mobile robot (AMR) able to navigate the area around the assembly station and safely carrying the collaborative robotic manipulator.
The chosen resource is the MiR 250 developed by Mobile Industrial Robots (Fig.7).

Figure 7 AMR MiR 250

Source: 1 https://www.mobile-industrial-robots.com/it/solutions/robots/mir250/

The MiR 250 is a flexible mobile robot that can easily carry a robotic manipulator and safely follow the worker alongside all the activities involved in the process. It has been chosen considering parameters of relevance for its specific application, such as maximum speed, battery capacity or embedded safety functions. Its relevant technical specifications are summarized in table A.1

3.1.2 Collaborative Robot Manipulator

Considering that for a collaborative manipulator the relevant specifications that shall be taken into account for the choice are several, together with the fact that recently the market offer of collaborative robots has significantly enlarged, a systematic evaluation procedure has been conducted in order to ensure the deployment of the most suitable robot for this case scenario.

Since a wrong selection of the robot can negatively affect the productivity and the ergonomics of the manufacturing process, a simple and systematic tool is developed through the Office Suite in order to guide the decision-making process.

The approach chosen to carry out the comparative analysis between collaborative manipulators available on the market is thus a multi-criteria decision-making method (MCDM) as developed by Chatterje et al [8]. to rank industrial robots for general industrial applications. The VIKOR (short for "multi-criteria optimization and compromise solution", in Serbian) is a method established to solve problems featuring conflicting decision criteria with different units, assuming that when an optimum solution cannot be reached compromise is then acceptable. The result of the application of the VIKOR method is a ranking of the best solutions from a finite set of alternatives with conflicting criteria, proposing a compromised solution.

Given the specific possible use of the cobot for this manufacturing case study, the technical specifications that have been chosen for the comparative analysis are:

- Payload: that is the maximum load that the robot can manipulate (including the weight of the gripper)
- Reachability: that is the maximum working volume of the robot

- TCP maximum speed: that is the maximum velocity that can be reached by the end-effector of the manipulator
- Repeatability: that is the ability of the robot to repeatedly position itself when asked to perform a certain task multiple times.
- Robot's weight: that is the weight of the robotic manipulator alone.

Considering the above-listed criteria chosen for the analysis, a short list of popular collaborative robots is provided in Table 4 along with their technical details.

Table 3 Collaborative Robot alternatives for VIKOR

Robot Name	Manufacturer	Payload [kg]	Weight [kg]	Reach [mm]	TCP Speed [mm\s]	Repeatability [mm]
LBR iiwa 7 R800	KUKA	7	22,3	800	1000	0,1
CRX10iA	FANUC	10	39	1249	1000	0.05
CRB 15000 GoFa	ABB	5	27	950	2200	0,05
UR5 CB3	Universal Robots	5	18.4	850	2000	0,03
RACER 5 0.80	COMAU	5	34	809	1000	0,03

After short-listing the robots, second step for the development of VIKOR method is to assign weights to the robot selection criteria The selected criteria are estimated with a simplified application of theAnalytical Hierarchical Process (AHP) . [29], given its simplicity and flexibility

The AHP is a quantitative analysis method that allows to derive weights for a short list of selected criteria through the development of a decision matrix, where relative importance of the selected criteria is assigned subjectively.

The decision matrix is developed by building a pair-wise comparison matrix ranging from 1 to 9 (intensity of importance), where 1 stands for "equally-preferred" whereas 9 expresses and extremely preferred status.

The final decision matrix for the specific assembly scenario is reported at Table 5.

Table 4 Cobot Ranking AHP Decision Matrix

	Payload	Reach	Repeatability	Weight	TCP Speed
Payload	1	1/8	1/2	3	1/4
Reach	6	1	3	8	1/3
Repeatability	2	1/3	1	3	1/4
Weight	1/3	1/9	1/3	1	1/4
TCP Speed	4	3	4	4	1

In order to estimate the priority of the variables, a vector of weights must be derived from the developed decision matrix, given the subjectivity of the choice of list of collaborative robots considered and of the decision matrix, a simplified application of the AHP using a root square scale approach is used.

To this aim the non-normalized vector of weights "w" is derived from the decision matrix "D" as follows:

$$\mathrm{w_j} = \sqrt[n]{\prod_{j=1}^{M}(\mathrm{D_{ij}})}$$

(3. 1)

i = 1,2,…,N: j = 1,2,…,M

Where M is the number of criteria and N is the number of cobots alternatives. The resulting vector of weights, already normalized, is thus:

$$w = \begin{Bmatrix} 0{,}085 \\ 0{,}32 \\ 0{,}13 \\ 0{,}046 \\ 0{,}42 \end{Bmatrix}$$

After applying the AHP and deriving the vector of weights for the selection criteria, third and last step of the application of the VIKOR method consists in determining the best, $(m_{ij})_{max}$ and the worst $(m_{ij})_{min}$ values for all the criteria and calculate E_i and F_i values according to the following:

$$E_i = \sum_{j=1}^{M} \left\{ \frac{w_j \left[(m_{ij})_{max} - m_{ij} \right]}{\left[(m_{ij})_{max} - (m_{ij})_{min} \right]} \right\}$$

(3. 2)

$$F_i = Max^n of \left\{ \frac{w_j \left[(m_{ij})_{max} - m_{ij} \right]}{\left[(m_{ij})_{max} - (m_{ij})_{min} \right]} \right\}$$

(3. 3)

Eq.(3.3) is only applicable to beneficial attributes (a higher value is preferred); for non-beneficial attributes the following relationship must be used instead:

$$E_i = \sum_{j=1}^{M} \left\{ \frac{w_j \left[m_{ij} - \left(m_{ij}\right)_{min}\right]}{\left[\left(m_{ij}\right)_{max} - \left(m_{ij}\right)_{min}\right]} \right\}$$

(3. 4)

And as a last step, using the values of E_i and F_i, calculate P_i values as follows:

$$Pi=vc-Ei-min(Ei-max-Ei-min)+1-\mathrm{vF}i-Fi-min\mathrm{F}i-max-Fi-min$$

(3. 5)

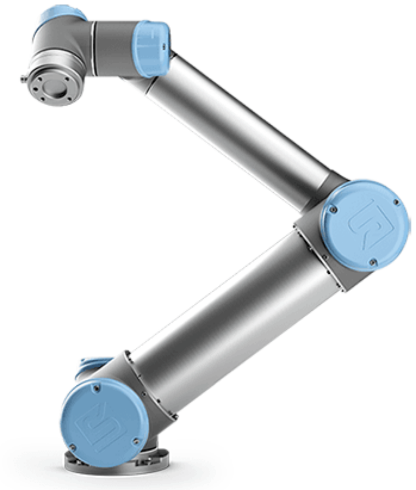
Where E_{i-max} and E_{i-min} are respectively the maximum and minimum value of E_i and F_{i-max} and F_{i-min} are respectively the maximum and minimum value of F_i. The value of "*v*" lies between 0 and 1, the compromise is selected with "voting by majority" (v>*0,5*), with "consensus" (*v* = 0,5) or with 'veto" (*v* < 0,5). Given that the pair-wise comparison matrix was developed subjectively, the value assigned to the variable is *v* = 0,25. The results of the analysis and the final ranking of the selected cobots is reported in Table 5:

Table 5 Cobots comparative analysis results and ranking

Robot	E_i	F_i	P_i	Rank
KUKA LBR iiwa 7 R800	1,05	0,42	0,7	5
FANUC CRX10iA	0,50	0,42	0,54	3
ABB CRB 1500 GoFa	0,35	0,21	0,19	2
Universal Robot UR5 CB3	0,44	0,28	0	1
COMAU RACER 5 0.80	0,85	0,43	0,64	4

Thus, as a result of the comparative analysis between the collaborative robots listed, the selected robot for the case study is the UR5 by Universal robots (Fig. 7)

Figure 8 Collaborative Robot UR5



Source: 2 https://wiredworkers.io/product/ur5/

3.1.3 End-Effector

For the successful deployment of a collaborative robot in a final assembly scenario the choice of the right end-effector (either one or multiple) is of a key importance. It is in fact the end-effector that ultimately defines the cobot’s payload, reach and capability to effectively grasp and handle the assembly components according to the gripping force and the number of fingers.

Considering the broad range of applications and properties of robot’s end-effectors, as well as a broad market offer, it is neither possible nor convenient to develop a comparative tool to evaluate a list of end-effectors representative for the available solutions. For these reasons the choice for the end-effector was carried out by analyzing the properties of the parts to be handled (Table.1), the characteristics of the assembly tasks involved (Table. 2) and finally of the video recordings.

The result of this analysis is that the process and the parts require a gripper type of end-effector with a medium-high flexibility capability; the payload allowed is not found to be a binding constraint, as the heaviest part weights 1,3 kg (2,5 lb). What is found to be a binding constraint are the variety of shapes and materials, as the parts to be handled are extremely different one from the others, including components with fragile glass surfaces, medium-flexible plastic and also rubber elements, which require a high haptic sensibility to be effectively handled by the robot.

Taken into consideration the above listed consideration, the end-effector that was found to offer a good compromise between the different requirements is the. 3-Finger Adaptive Robot Gripper by ROBOTIQ, whose technical details are reported in A.2.

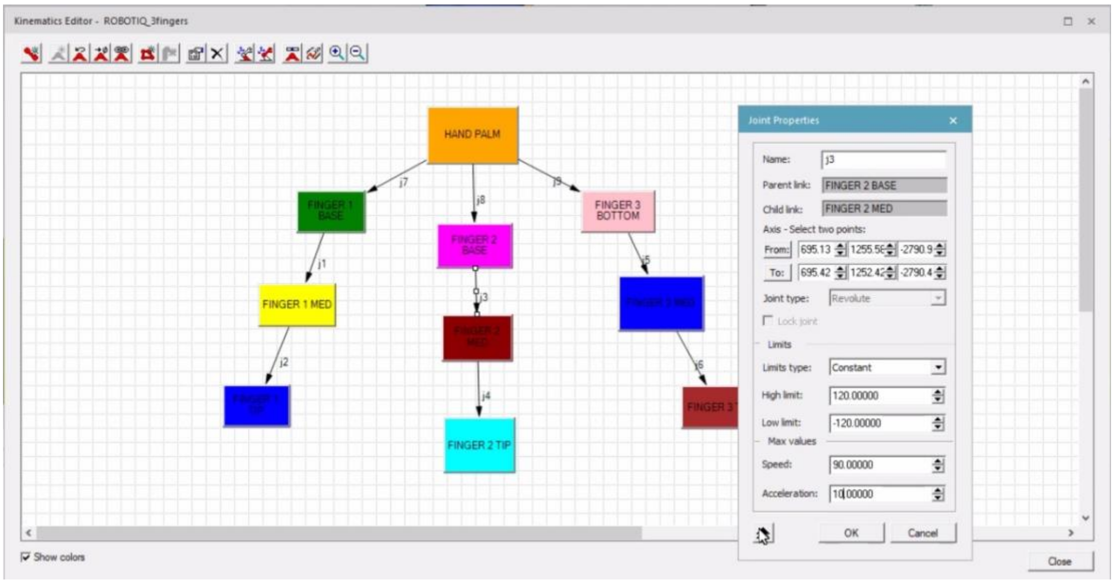
3.2 Simulation Setup

As previously mentioned, the development of the digital twin has been carried out in the virtual simulation environment of Tecnomatix Process Simulate, which allows to perform both robot and human operation within the same environment.

The creation of the study begins by importing the CAD files that will be utilized during the study, which include the models of the six assembly components to be assembled, the prototype of the transportation cart which carries the door frame and finally the two power-screwdrivers specifically needed for the screwing operations. Importing the collaborative robot as a .jt file allowed to have in the simulation a model of the collaborative manipulator with the joint kinematics (joints limits and velocities) already embedded.

However, no such feature is available for the robot gripper, it is thus necessary to import the CAD model and then define the kinematics of the elements of the grip through the ‘kinematic editor’ tool available in the software (Fig.9)

Figure 9 Robot Gripper Kinematic Definition



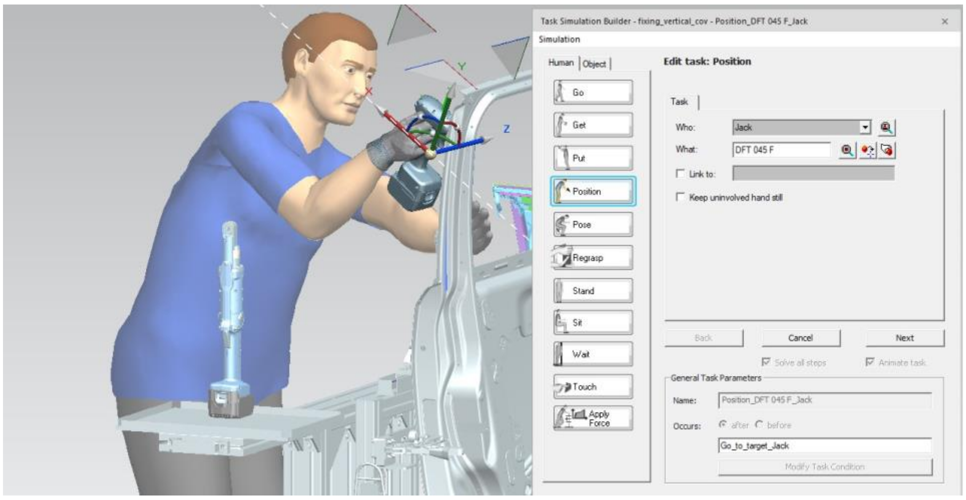
Name: j3
Parent link: FINGER 2 BASE
Child link: FINGER 2 MED
Axis - Select two points:
From: 695.13 1255.56 -2790.9
To: 695.42 1252.42 -2790.4
Joint type: Revolute
☐ Lock joint
Limits
Limits type: Constant
High limit: 120.00000
Low limit: -120.00000
Max values
Speed: 90.00000
Acceleration: 10.00000

Through this tool it is possible to embed in the simulation not only the kinematics but also the technical parameters of the gripper as reported in Table A2. The last input resource for the simulation study is the human worker, who will be used to simulate the manual process and the collaborative one to allow for a proper comparison, as a comparative analysis between a collaborative simulation and the video-recording of the manual process might lead to unreliable results.

For this study it was decided to use a male Jack from the ANSUR II database (which is a US army human database) featuring a 50-percentile height (175 cm), a 50 percentile weight (79 kg) and a walking speed of 1 m/s.

After defining the features of the human worker, to simulate the tasks carried out manually it is used a software tool called “human Task simulation builder ” (Fig.10).

Figure 10 Human Task Simulation Builder Tool



Task Simulation Builder - fixing_vertical_cov - Position_DFT 045 F_Jack

Edit task: Position

Who: Jack

What: DFT 045 F

☐ Link to:

☐ Keep uninvolved hand still

☑ Solve all steps ☑ Animate task

General Task Parameters

Name: Position_DFT 045 F_Jack

Occurs: ● after ○ before

Go_to_target_Jack

The task simulation builder allows to define basic human activities, such as walk to a location, get, position, and place an object or apply a force, which must then be refined manually by manipulating the mannequin.

In this regard other advanced analysis tools available in the virtual environment will allow to derive ergonomics and safety reports (Chapter 6) which will be used for the final comparative analysis between the two manufacturing scenarios.

3.3 Manual Assembly Simulation analysis

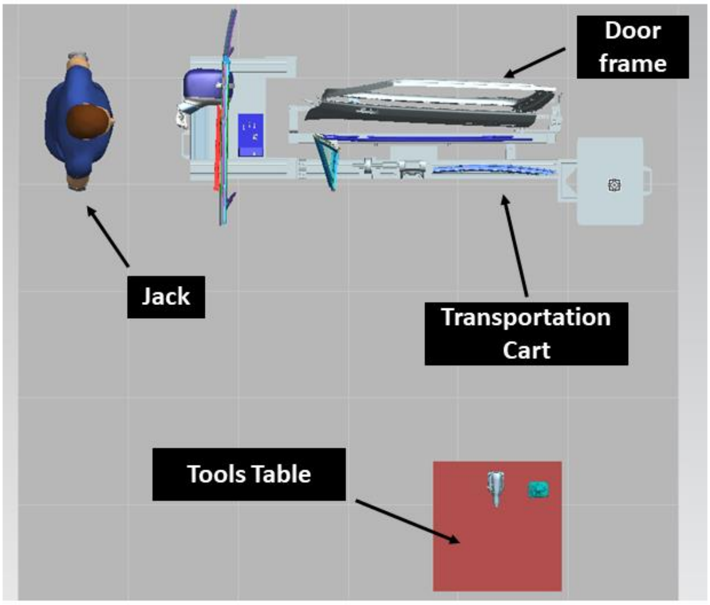
The aim of this section is to simulate in a representative way worker’s tasks, this in order to make possible a reliable comparative analysis between the manual and the HRC scenarios. To this aim the video-recording of the manual assembly is used as a reference for the definition of the human simulated tasks.

In this scenario the layout of the workstation is fairly simple: as it can be seen in Fig. 11 the main component of the assembly cell is a transportation cart which carries the door frame. The assembly parts are directly fed on the transportation cart prior the cart is pulled to its working location and the wheels are blocked for assembly.

3.3.1 Time analysis

The manual operations times, designed through the task simulation builder tool, are defined according to the MTM procedure; the results of the time analysis breakdown are reported in Table 6.

Figure 11 Workstation Layout (Manual Assembly)



Considering the latter, it is possible to notice from Table 6 that a single manual assembly cycle carries a walking time, which is an example of NVAA, of 47,5 seconds, which represents the 20% of the whole cycle time and a total of 93 minutes of productivity loss in a 8-hours work shift.

Table 6 Cycle Times Manual Operations Workcell 1

Assembly Operation	Cycle Time [s]
Mounting and fixing front glassdoor	45,9
Mounting and fixing posterior vertical coverage	29,4
Insertion of front doorseal	68,7
Insertion of anterior vertical coverage	17
Insertion of window waterstrip	21,3
Insertion of left rearview mirror	13,7
Walking activities	47,5
Total manual assembly cycle time	243,5

3.3.2 Ergonomic evaluation to orient HR task distribution

One of the research questions raised in the introduction to study concerns the possibility to enlarge the scope of the parameters considered in the proposed task classification logic, also including an evaluation of the physical strain to which the worker is subjected. By performing an ergonomic analysis through the tools available in Process Simulate, it would thus be possible to identify the most strenuous activities for the operator and hence earn a better understanding of the tasks that could benefit the more from total or partial automation and thus orienting the HR task distribution.

There are several methods available to assess the ergonomics of a manual process, two parameters to consider in order to choose the most suitable one for the analyzed manufacturing scenario are the masses of the parts/tools handled by the operator in the working cycle and the body parts mostly involved. This because different ergonomics assessment methods may focus on different body parts, for instance some focus on back postures and lifted weights (OWAS, EWAS), while others consider the energy expenditure of the worker and his/her fatigue.

For these reasons to evaluate the potential ergonomic risk for the worker it is used the "Ergonomics Metrics" available in the simulation environment. Its main feature is to compute, given a human operation, the percentages of the cycle time that the most important body joints spend in each posture category, categorized in mild, moderate and significant discomfort, given angle thresholds according to the Standard ISO 1005. The result of the evaluation is reported in Table 7, where for each assembly activity (columns) the percentages of cycle time that each body joint spends in moderate (orange columns) and significant (red columns) discomfort posture category. As it was foreseeable by the kind of activity involved, the body joints that spend the most time in ergonomically uncomfortable postures are the wrists, right shoulder and right elbow (the human worker is supposed to be right-handed).This is due to the fact that most of the part handling and positioning takes place at waist level, thus not forcing body regions like back or neck to demanding postures. On the contrary, several screwing operations (through a power-screwer) may lead to prolonged fatigue of the upper right limbs, due to the continuous carrying of the tool and to the screwing locations.

3.3.3 Limits of a holistic HR task allocation approach

By analyzing the results of the application of a holistic common logic when approaching the problem of HR task allocation, the aim is to show the limits and the weaknesses of an unstructured framework. This is done by carrying out a comparative analysis between the results obtained with an approach based on "common sense and the ones obtained through the proposed systematic allocation method, which is the main goal of this study.

The 'common sense' logic used for the first hybrid assembly scenario is to cut down on the NVAA (Non Value Added Activities), i.e. those activities that do not add any customer value to the final product (i.e. walking, handling activities, idle times).

Hence, in this scenario the cobot has sort of a "slave role", being assigned mostly handling activities (pick, handle and or place tools) or presenting the parts to be assembled to the worker in comfortable locations.

The results of this new scenario shows a decrease in the cycle time of 29 s, with a consequent improvement in the efficiency of 12,30 % with respect to the manual assembly. This also leads, assuming a work shift of 8 hours, an increase in total assembly completed per shift from 120 to 137.

Table 7 Manual workcell 1 time percentages posture categories

		Insertion Front Glassdoor		Front Glassdoor Screw #1		Front Glassdoor Screw #2		Insertion Posterior Coverage		Posterior Coverage Screw #1		Posterior Coverage Screw #2&3		Fitting Doorseal Front		Fitting Doorseal rear		Insertion Anterior Coverage		Insertion Waterstrip		Insertion Rearvie Mirror	
		M	H	M	H	M	H	M	H	M	H	M	H	M	H	M	H	M	H	M	H	M	H
Neck	Flection	3	3	4	6	22	29	11	10	8	16	31	20	1	0	13	0	15	0	23	17	11	19
	Extension	19	0	0	0	1	3	15	0	0	0	1	0	29	48	22	0	13	0	0	0	0	0
	Rotation	87	0	10	1	23	17	39	8	6	8	31	11	68	0	45	13	63	12	31	2	15	5
	Lat. Bend	0	0	4	0	20	0	0	0	5	4	19	0	21	0	0	0	13	0	3	0	5	2
Back	Flection	61	0	2	0	12	2	19	0	0	0	32	0	41	0	9	0	42	0	16	0	0	0
	Extension	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0
	Axial twist	0	0	0	0	14	0	0	0	8	0	1	0	17	0	0	0	3	0	0	0	3	0
	Lat. Bend	0	0	0	0	16	0	2	0	0	0	2	0	0	0	0	0	5	0	0	0	0	0
Right Wrist	Flection	12	79	38	0	17	2	12	36	5	0	15	36	18	33	0	0	22	2	17	1	4	7
	Extension	0	0	3	0	6	5	29	2	20	0	23	0	13	9	32	33	27	0	33	7	42	20
	Sup/Pron	1	0	1	1	15	3	20	27	15	29	28	0	47	19	6	74	8	16	45	8	14	5
	Ulnar/Rad	10	14	38	2	4	32	8	84	10	0	5	59	14	25	10	55	18	37	26	28	10	14
Left Wrist	Flection	0	0	6	0	8	57	25	9	13	25	45	19	13	12	29	0	2	1	36	19	33	15
	Extension	86	4	10	0	8	16	45	1	8	0	15	0	14	9	35	14	60	15	2	0	8	20
	Sup/Pron	61	24	9	0	42	20	64	1	32	0	33	7	34	4	36	40	44	3	36	2	16	41
	Ulnar/Rad	3	10	35	49	4	59	15	58	23	0	34	22	38	17	27	36	22	45	20	48	17	53
Right Shoulder	Flection	77	0	47	0	45	14	14	38	29	0	46	0	26	0	65	0	31	14	65	5	53	15
	Extension	27	65	83	0	43	42	60	16	21	0	42	19	21	1	76	0	66	1	51	3	60	11
	Abduction	89	0	35	0	14	0	56	0	0	0	70	0	15	58	60	15	33	28	21	0	8	0
	Rotation	7	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0
Left Shoulder	Flection	0	0	0	0	4	0	5	0	0	0	0	0	2	30	27	0	1	0	3	0	0	0
	Extension	88	3	47	1	49	4	82	13	17	17	84	0	41	2	61	2	64	0	75	2	42	31
	Abduction	89	0	37	0	8	0	26	24	3	5	18	0	15	57	61	0	54	14	21	0	4	0
	Rotation	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L Elbow	Flection	12	0	32	0	37	0	9	24	0	0	0	0	2	21	0	0	0	14	3	0	1	0
R Elbow	Flection	90	4	44	9	28	2	65	2	45	0	28	11	22	0	80	0	67	2	50	0	24	27

However, even though this preliminary analysis already shows a significant potential improvement in the productivity of the cell, no significant ergonomic improvement is achieved, as walking activities and small handling operations of light objects do not constitute a relevant physical effort for the worker.

Moreover, the time analysis of the two resources shows that the collaborative robot spends approximately the 20% of the cycle time in idle times, thus leading to a under-exploitation of the robot.

Aim of the next section will be thus to deal with the above-mentioned issues, developing a systematic task allocation procedure able to distribute the tasks between human and robot in such a way that the inefficiencies are minimized and concerns around safety and HR interaction are considered.

CHAPTER FOUR

DEVELOPMENT OF A NEW TASK ALLOCATION METHOD

This section will deal with the main objective of the whole research, that is to propose a new systematic methodology to assess the automatability of a task in a simple and intuitive way. In order to allow for an effective way to assess whether a task shall be automated or not, the idea is to evaluate the effectiveness or suitability of that task by developing a scoring system of look-up tables based on the characteristics of a manufacturing assembly task.

These look-up tables are built following the identification, through considerations around the developed digital twin and the study of the process and the existing literature, of the variables that have a primary effect on the feasibility for automation and the productivity of the assembly cell. These variables are then broken-down into more specific sub-variables that could describe the features of a collaborative assembly task in a more complete way.

As a last step, to each of the sub-variables is assigned a short set of describing criteria (from two to four), to allow for an easy understanding and scoring of each task.

As a final step, an objective function is developed in order to turn the multiple values coming from the evaluation through the look-up tables into a final value that automatically allocates the task to the human or to the robot.

4.1 A new task allocation methodology

4.1.1 First Variable: Part & Task Characteristics

The first variable considered are the physical properties of the part/tool to be handled and the characteristics of the task to be carried out. These features shall be considered in the task allocation process because they have a direct impact on the actual capability of the robot to perform a certain activity. The physical properties, such as weight, part texture, geometry, dictate the requirements for the robots gripper and possibility or necessity to adopt multiple grippers if the requirements cannot be met by a single one, with consequent idle times for the end-effector change.
On the other end, the characteristics of the task describe the technical specifications of the collaborative manipulator, e.g. accuracy required, dexterity or the necessity to apply a force to carry out a task.

The logic behind the look up tables is the same one for each variable, that is to derive a set of describing criteria associated to a set of possible scores between 0 and 1 (where 0 stands for … and 1 stands for …)

The developed look-up table of sub-variables and describing criteria is reported in Table 8.

Table 8 HR Task Assignment: Task/Part Characteristics Look-Up Table

Sub-Variables	Criteria	Examples & Description	ID
Part/Tool Weight	$w < 1$ kg	/	A1.1
	1 kg $< w <$ 3 kg	/	A1.2
	3 kg $< w <$ 5 kg	/	A1.3

Sub-Variables	Criteria	Examples & Description	ID
	w > 5 kg	/	A1.4
Part Texture	Part is rigid, force applied by end effector is not a concern	e.g. steel elements, bolts, nuts	A2.1
	Part can be deformed under high force, shape restores itself after force application		A2.2
	Part deformed under low force, shape needs to be adjusted after robot handling		A2.3
	Part is shapeless		A2.4
Part Fragility	No fragile surface, not broke nor by high energy impact or crush		A3.1
	Can be indented or broken if crushed or impact at high force	Tools, thin metal coponents	A3.2
	Can be indented or broken if crush or impact at low energy	Bulky metal components, rubber elements	A3.3
	Can be indented or broken simply by the gripping force of the end-effector	Glasses, mirrors	A3.4
Gripping Texture	YES		A3.5
	NO		A3.6
Task dexterity	Simple operation, precision not required, only rigid motions involved	Pick up & place, hold component	B1.1
	Some flexibility required to end effector, positioning requires some adjustments	Pre-positioning of components, handling tool to worker	B1.2
	High precision required, involved tolerances, low haptic sensibility		B1.3
	High levels of dexterity and flexibility required		B1.4
Tactfulness Required	YES	Fitting of rubber seals, adjust components with fingertips	B2.1
	NO		B2.2

Sub-Variables	Criteria	Examples & Description	ID
Application of force required	YES		B2.3
	NO		B2.4

4.1.2 Second variable: Human-Robot Communication

The second variable that was found to have a primary effect on productivity, and thus considered for the proposed new task assignment method, concerns the kind of communication required between human and robot in order to carry out a specific task.

The assembly scenario under study features an intensive and continuous collaboration between the two resources, requiring an effective communication at any time. Most Importantly a proper HR communication shall grant a safe environment for the worker, allowing him/her to be aware at any time where the robot is and what task it is currently performing. On the other hand, the cobot must be able to know at every time the current status of the ongoing process and worker's location. The solutions available on the market are several and the combinations are countless; vision-based technologies applied to human-robot interaction are proving to be efficient due to high level of collaboration, easy installation and tailoring and their speed [30].

Another recent development in the field of human-robot collaboration is the use of Augmented Reality (AR) software that allow the worker to visualize important information like robot's working trajectories and paths, sequence of actions and graphical instructions, this with the aim to enable a natural Human-System and System-Human interaction and design a system that can worker can trust. [31] [32].

The state of the art for the design of a human-robot intensive collaboration in real manufacturing environment features what is called a multi-modal interface collaboration, i.e. a network of different devices and communication protocols (e.g. smartwatch or smartphones, AR, motion or speech recognition) , examples of effective design and deployment of HR multimodal communications are [31][32].

Although examples of comparative analysis of the performances of different kind of communication devices [30] exist and first metrics for human-robot communication have been developed, to the author's knowledge no human-robot task assignment methods that consider the characteristics of human-robot communication can be found in the literature.

Hence, one of the novelties of this study is the development of a HR communication look-up table that list the most influential features of a communication-enabling technology, in relation to what the task requirements are and in comparison, to different enabling devices, and assigns score accordingly.

The result of this analysis is reported in Table 9.

Table 9 HR Task Assignment - HR Communication Look-Up Table

Sub-Variable	Criteria	Examples or Description	Score
Interaction required	No interaction of any kind required	Motion recognition	C1.1
	No physical Interaction required	Verbal or sound command used	C1.2
	Physical Interaction – No Walking required	Wearable devices like smartphones or smartwatch	C1.3
	Physical Interaction – walking required	Fixed screen	C1.4

Cognitive effort	High cognitive effort	Head mounted speech recognition, AR glasses	C2.1
	Moderate Cognitive Effort		C2.2
	Low Cognitive effort	Glove based gesture or distant speech recognition	C2.3
Instruction Details Requirements	Simple command	Next, Stop, Go	C3.1
	Data messages/ highlighting messages	Point out part to be handled or where to collect it	C3.2
	Demonstration or guidance messages	Teach a movement, show the worker hot to perform a task	C3.3
Processing Time (Compared to different technologies)	High Processing Time	Hard buttons or joistck	C4.1
	Medium processing time		C4.2
	Low processing time	Soft AR buttons, gesture recognition, haptic sensors	C4.3
Affected by noise	YES		C5.1
	NO		C5.2
Affected by visual obstruction	YES		C5.3
	NO		C5.4

4.1.3 Third Variable: Workstation Safety Requirements

The third variable that is considered for the proposed task allocation method considers the characteristics that play a primary role in the identification of possible hazards specifically related to a task.

The logic behind the choice to consider safety as a decision variable aims at providing in the early stage of design an assessment on the possible risks deriving by assigning a specific activity to the robot, or to carry out it jointly. In this perspective, a more critical task will need more strict and advanced safeguards in order to grant worker's safety, with subsequent effects on the productivity of the cell and development costs.

As mentioned in the introduction, one of the criticalities in designing and implementing a collaborative assembly cell is that the inefficiencies brought by a complex safety system does not overcome the efficiencies of adopting a collaborative robot, making its deployment not convenient. Hence, assigning a dangerous task to the robot, with a subsequent appropriate safeguard to allow for it, may eventually result in unacceptable efficiencies losses.

The task safety describing criteria considered relevant to the aims just presented are then gathered and listed in a look (Table 10).

4.1.4 Fourth Variable: Feeding Systems

The fourth and last variable considered relevant for the decision process regards the characteristics of the way the different parts, component and tools are presented to the worker during the assembly process. The reason why this can heavily affect the production cycle time and the suitability of the robot is dual.

From one side the physical characteristics of the parts are what define how they can be presented to the worker; the components involved in this case study are extremely different in shape and size, not allowing for an ordinated kitting and to present them at the same location.

Table 10 HR Task Assignment - Workstation Safety Characteristics

Sub-Variable	Criteria	Examples/Descriptions	Score

Part/Tool Shape	No Sharp edges, no entangling chances, soft material	D1.1
	No sharp edges, low chance of entangling, friction with part might occur	D1.2
	Presence of sharp/ cutting edges tool	D1.3
Possible Hazards Involved	No hazards identified	D2.1
	Low energy impact, transient contact, easy to avoid	D2.2
	High energy impact or pinching, difficult to evade the contact	D2.3
	Cutting or bruises, high energy quasi-static impact	D2.4
Distance Robot-Worker	Worker inside robot reachability zone, interaction not expected	D3.1
	Worker inside robot's reachability area, interaction is expected	D3.2
	Worker inside robot's warning volume	D3.3
	Worker outside robot's warning volume	D3.4

The consequences of this kind of feeding are several inefficiencies due to NVAA of walking around the cart to reach the different parts and tools locations.

On the other side, the way components are fed is of a key importance for the actual capability of the robot to find them and effectively handle them. If for instance a component is fed at a precise position and orientation in every cycle, and the components are kitted so that same parts are together, the robot just needs to know the location to find and handle the part. On the contrary if the parts different in shape, size and color are presented without an order, the robot will need advanced vision and sensor systems to detect the right part, with a consequent higher possibility of error and increased cycle time.

The resulting describing criteria of the considerations just presented are reported in Table 11.

Table 11 HR Task Assignment: Feeding System Features

Sub-variable	Criteria	Example & Description	Score
Walking Distance	Longer than 30 ft (9 m)		E1.1
	Between 16 ft (5 m) and 30 ft (9 m)		E1.2
	Between 3 ft (1 m) and 16 ft (5 m)		E1.3
	Distance lower than 3 ft (1 m)		E1.4
Feeding Mode	No sorting, parts of different shape and size are fed through belts or container without an order		E2.1
	Parts are sorted, fed through belt or containers without an order		E2.2
	Parts are kitted, position and orientation cannot be precisely defined		E2.3
	Parts are kitted and fed at defined position and orientation		E2.4

4.1.5 HR task allocation Objective function

To provide an effective and intuitive way to evaluate the suitability of a task for collaborative automation, an objective function has been defined with the aim to obtain a final "suitability for automation score" for each task in the early stages of design.

This final score shall be obtained by means of a Multi-Criteria Decision-Making (MCDM) function, i.e. the result of the objective function is given by the evaluation, performed by means of the look-up tables developed, of the four decision variables described in the previous four subsections.

To each of the decision variable is associated a weighting factor, according to their reciprocal importance, in order to assess the task suitability for automation. The weighting factors are designed so that their values are between 0 and 1, while their sum is 1.

The objective function build for the case study is thus the following:

$$SCA = PTw_{pt} + HRCw_{hrc} + SCw_{sc} + FSw_{fs} \tag{4. 1}$$

Where:

- SCA: Suitability for Collaborative Automation
- PT: Part/Task characteristics
- HRC: Human-Robot Communication
- SS: workstation Safety System features
- FS: Feeding system characteristics
- w_x: weighting factor

In order to appropriately define the weighting factors, a quantitative analysis, performed by means Analytical Hierarchy Process (AHP), is carried out. For this study the AHP is applied as proposed by [33].

After identifying the problem and defining the criteria (decision variables) that shall be compared, the following step is to define a comparison scale for AHP preference, which for this study ranges from 1 to 9 (intensity of importance). In this scale, 1 expresses the equally-preferred status, while 9 expresses the extremely-preferred status. The following action is then to construct a pair-wise comparison matrix for the four decision variables, aiming at showing the importance of one criterion over the others (Table 12).

Table 12 Task Allocation AHP Decision Variables Comparison matrix

Task Allocation decision variables	Workstation Safety characteristics	Part/task Characteristics	Human-Robot Communication	Feeding System
Workstation Safety characteristics	1	4	5	5
Part/task Characteristics	1/4	1	4	3
Human-Robot Communication	1/5	1/4	1	2
Feeding System	1/5	1/3	1/2	1

As it can be seen, the results coming from the questionnaire, whose structure and analysis will be presented in the next sub-chapter, show that safety has the highest importance, followed by the characteristics of part/task, HR communication and finally the features of the feeding system.

To verify the reliability of the values obtained through the survey, and derive the weighting factors, the following step is to synthesize the comparison matrix by dividing each element of the matrix by its column total (Table 13).

Table 13 Task Allocation AHP Decision Variables Synthesized Comparison matrix

Task Allocation decision variables	Workstation Safety characteristics	Part/task Characteristics	Human-Robot Communication	Feeding System

Workstation Safety characteristics	0,61	0,72	0,48	0,45
Part/task Characteristics	0,15	0,18	0,38	0,27
Human-Robot Communication	0,12	0,04	0,09	0,18
Feeding System	0,12	0,06	0,05	0,08

Finally, the priority vector of the weighting factors is derived by calculating the average of each row of the synthesized matrix.

The priority vector of the weighting factors for the decision is given below.

$$v = \begin{bmatrix} 0{,}56 \\ 0{,}25 \\ 0{,}11 \\ 0{,}08 \end{bmatrix}$$

However, since the comparison matrix comes from a subjective group decision, the validity of the reciprocal importance assigned to the decision criteria shall be verified. To this aim, the consistency of the analysis comparison can be determined by calculating a consistency ratio (Eq. 4.3).

$$CR = \frac{CI}{RI} \tag{4. 2}$$

While RI is a predefined factor depending on the size of the pair-wise comparison matrix, which for a 4 x 4 matrix is equal to 0.9, CI is calculated according to Eq. 4.3

$$CI = \frac{(\lambda_{max} - n\ )}{n - 1} \tag{4. 3}$$

Where λ_{max} is the maximum eigenvalue and is the size of the comparison matrix.

$$0{,}56\begin{bmatrix}1\\1/4\\1/5\\1/5\end{bmatrix}+0{,}25\begin{bmatrix}4\\1\\1/4\\1/3\end{bmatrix}+0{,}11\begin{bmatrix}5\\4\\1\\1/2\end{bmatrix}+0{,}08\begin{bmatrix}5\\3\\2\\1\end{bmatrix}=\begin{bmatrix}2{,}50\\1{,}07\\0{,}44\\0{,}33\end{bmatrix} \tag{4. 4}$$

By dividing all the weighted sum matrix elements, obtained by Eq 4.4, by their priority elements as below:

2,50/ 0,56 = 4,4377

1,07/ 0,25 = 4,3444

0,44/ 0,11 = 4,012

0,33/ 0,08 = 4,1269

The λ_{max} can be calculated as the average of the above found values:

$$\lambda_{max}=\frac{4{,}4377+4{,}3444\ +\ 4{,}012+4{,}1269}{4}=4{,}2303$$

And finally it is possible to evaluate CI and CR according to 4.2 and 4.3:

$$CI=\frac{(\lambda_{max}-n\,)}{n-1}=\frac{(4{,}2303-4)}{4-1}=0{,}7676$$

$$CR=\frac{CI}{CR}=\frac{0{,}7676}{0{,}9}=0{,}085$$

According to [33] and the existing literature related to the Analytical hierarchy process, the subjective judgements for a pair-wise comparison matrix can be considered acceptable if the critical ratio is less than 0,1, which is the case under study.

Hence, the results coming from the questionnaire regarding the AHP comparison matrix can be considered reliable; thus the weighting factors of the priority vector can be associated to the decision variables in the multi-criteria objective function in order to assess the suitability for automation of a task.

4.2 Proposed HR Task Allocation Validation

As mentioned in the introduction to this study, when evaluating the complexity of a task for its possible automation, in most of the available studies this is done by means of subjective considerations coming from the authors. While some parameters can be assessed objectively, e.g. dimension of the part compared to the gripper's stroke or speed and force reduction according to the standards [21], other characteristics of key importance, such as the dexterity required for a task, can be assessed only through personal experience and the analysis of the manufacturing scenario.

To partially solve the issue of subjectivity, a further novelty of this this study is the development of a technical questionnaire tailored on automation for collaborative assembly. This questionnaire has been then handed to experts and researchers belonging to the field of robotics, to allow for reliable and objective results.

Then, the next two sub sections of the present chapter will present the structure of the questionnaire (4.2.1) and the analysis and validation of its results (4.2.2)

4.2.1 Questionnaire development for HR task analysis

The aim of the questionnaire developed for the present study is to derive, by means of robotic experts and researcher's opinions, an easy and intuitive score to be associated to each of the task describing criteria listed in the task allocation look-up tables developed (Table 8-11). To this aim, the candidates shall answer to a set of questions (items) which describe different situations that can be found in a human-robot collaborative assembly scenario.

To answer the question the candidate shall express a preference concerning the suitability, or actual possibility, to automate a task featuring the characteristics described in each question.

The questionnaire is thus divided into two main sections; the first one asking to evaluate the describing criteria listed in the look-up tables and the second one requiring to express an opinion around the four variables considered in the final task allocation objective function, in order to build the AHP comparison matrix for the decision variables (Table 12).

Concerning the collaborative assembly describing criteria, the Likert scale metrics is the approach chosen to evaluate candidate's perceptions and attitudes towards the presented case scenarios. A Likert scale is defined as "a set of statements (items) offered for a real or hypothetical situation under study" [34].

The concepts of Likert scale where applied following the prescriptions of Schrum et al [35], who performed a four years review of 110 HRI-related papers who made use of the Likert scale.

In their study the authors highlight the most common mistakes in the application of this metric and provide recommendations to improve the accuracy of conclusions drawn from Likert scale data.

The result is a first questionnaire featuring a total of 58 items divided in four sections, one for each decision variables. Following the recommendations of [35] for the Likert scale design, to each item are associated five numerical response alternatives (from 1 to 5), in which an individual must choose their level of agreement. For the present study the value 1 means that the related describing criterium would make the specific task "extremely not suitable or convenient for collaborative automation", while the alternative 5 indicates that the characteristics of the task make it "extremely suitable or convenient for automation".

Finally, the questionnaire is concluded by a shorter section of six items asking the individuals to assess the reciprocal importance of the four decision variables considered in the multi-criteria objective function [4.1.5]. For these final items the response scale (Staple Scale) ranges from 1/9 to 9, where 9 expresses the extremely preferred status and 1/9 expresses the extremely non-preferred status.

Before the submission of the questionnaire to the identified suitable candidates, it was reviewed and approved by the faculty advisors for this research. For a further validation, as part of the approval procedure the questionnaire was also reviewed by a work psychology Master student, to grant a more intuitive understanding of the items and its ethical correctness.

4.2.2 Questionnaire results validation and analysis

For the present survey three ideal categories of target individuals have been identified, to who the questionnaire has been sent: Robotics and Manufacturing Engineering MSc and Phd students, Robotics and Industrial Engineering college faculty members and finally experienced workers in the field of collaborative robotics and World Class Manufacturing (WCM).

The survey received a total of 23 answers from the above-mentioned categories, respectively 9 answers from experienced workers currently employed at STELLANTIS SPA, 8 answers from Robotics engineering college professors and lastly 6 answers came from automotive and robotics engineering PhDs and MSc students.

Since a poorly formed scale may result in data that do not assess the intended hypothesis, before applying any statistical test and analyze the final results of a Likert scale it is best practice to test the quality of the scale [34] [35].

To this aim, a common method is to apply the Cronbach's alpha to measure the internal consistency of the scale. A Cronbach's alpha of 0.7 is typically considered an acceptable level of intern reliability [36]. Cronbach's alpha is applied to make sure that all the items in a certain scale correlates, allowing to identify which sets of Likert items present a poor reliability and thus adopt post-hoc corrections.

Before applying Cronbach's alpha, the results coming from the evaluations of the Likert items, ranging from 1 to 5, have been converted to a scale from 0 (corresponding to the response alternative 1 of the questionnaire) to 1 (corresponding to the response alternative 5). In this way the final score coming from the task allocation coming from the objective function will be between 0 and 1.

Cronbach's alpha is evaluated in the according to the following:

$$\alpha = \frac{K}{K-1}\left[\frac{\left(s_x^2 - \sum s_y^2\right)}{s_x^2}\right] \tag{4. 5}$$

Where :

- K: is the number of test items
- $\sum s_y^2$: is sum of the item's variance
- s_x^2: is the variance of the total score

Since, as already mentioned, the aim of Cronbach's alpha is to test the quality of a Likert scale by measuring how strongly its elements are correlated, the alpha is calculated in the first place for each of the five sections of the survey, i.e. the four decision variables and the values for the AHP comparison matrix.

The result of the consistency analysis through Cronbach's alpha are reported in Table 13; the reliability level is assigned according to [37].

The reliability test reports that the survey section that shows the highest reliability ($\alpha = 0,8$) is the one inquiring the relative importance of the task allocation decision criteria for the AHP. It also shows that the two sub-sections investigating expert's opinion on automation suitability regarding Part/Task characteristics and HR communication requirements (respectively $\alpha = 0,76$ and $\alpha = 0,77$).

Table 14 HR Collaboration Survey - Reliability Test Results

Questionnaire sub-section	Alpha value	Level of reliability
Part/Task characteristics	0,76	Acceptable
Human-Robot communication	0,77	Acceptable
Workstation safety criticalities	0,51	Not Satisfactory
Feeding system features	0,61	Moderate
AHP comparison matrix values	0,80	Good

However, although the questions regarding the feeding system features show a questionable but still acceptable level of consistency, the reliability of the sub-section concerning HR safety presents a non-satisfactory level of reliability. A reason to explain this significant difference between this section and the others might lie in the fact that safety is one of the hardest criticalities when designing a collaborative workstation. Considering that the aim of the survey is to assess at the same time the actual possibility to automate a task on and its effective conveniency, the individual's choice to assign a heavier weight to the productivity benefits to automate a task over the possible safety consequences, or vice versa, may lead to completely opposite answers.

As a further statistical analysis of the results, a within-scale item correlation, to decide on the item relevance, has been carried out by computing and analyzing the Pearson correlation coefficient [38][36]. Pearson correlation can be applied in two different ways: as an Inter-item correlation, i.e. degree of correlation between items taken successively two-by-two, or Item-to-total correlation, i.e. degree of correlation between each item and the whole scale.

As in this study the survey has been tailored in such a way that the describing criteria are grouped in set of three to four items strongly associated, the inter-item correlation coefficient has been applied.

According to [39], if an item-to-item correlation has a value of 0,4 or lower, it means that the correlation between the two items is low, and the items shall either eliminated from the survey or further statistical analysis shall be carried out (e.g. Factor Analysis). Since several of the individuals who answered the survey considered the questionnaire as long and demanding, items with a correlation lower than 0,4 have been eliminated, with the aim to simplifying the questionnaire and reduce its length.

By computing the item-to-item Pearson coefficient for the first section (Part/Task Characteristics), it was found that question A1.4 correlates poorly with A1.3 (r=0,31), A2.2 has a low correlation both with A2.1 (0,41) and with A2.3 (0,39) and B4.3 shows a low correlation with B4.2 (0,20) and B4.4 (0,35). After removing the three above-mentioned items Cronbach's alpha is computed again and it has been found that the reliability has increased, going from a Cronbach's alpha value of 0,76 to 0,8.

In the second section of the survey, HR communication, it has been found that a strong correlation exists between all the items except for C4.1, which correlates poorly with C4.2 ($r = 0,32$) and C4.3 ($r = 0,09$). By removing it also the reliability of the sub-section changes, increasing from $\alpha = 0,77$ to $\alpha = 0,79$.

Sub-section three of the questionnaire, concerning the safety characteristics of the assembly station, shows that item D2.2 has an extremely low correlation with items D2.1 (0,14) and D2.3 (0,10) and that item D3.1 does not correlate with items D3.1 (0,21) and D3.4 (0,11). The two items have thus been eliminated.

Finally, the item-to-item correlation coefficient was computed for the question concerning the feeding system; it has been found that the item E1.3 has a poor correlation with E1.2 (0,21) and E1.4 (0,11), while item E2.3 shows a low Pearson coefficient related to items E2.2 (0,14) and E2.4 (0,15).

After eliminating the items that showed a low inter-item correlation with the other items in the same sub-section, Cronbach's alpha was computed again to check the reliability of the new questionnaire (Table 15)

Table 15 Questionnaire Reliability Results

Questionnaire Sub-Section	Cronbach's α (Old)	Cronbach's α (New)	Reliability (old)	Reliability (new)
Part/Task characteristics	0,76	0,81	Acceptable	Good
Human-Robot communication	0,77	0,79	Acceptable	Good
Workstation safety criticalities	0,51	0,54	Not Satisfactory	Not Satisfactory
Feeding system features	0,55	0,65	Not Satisfactory	Acceptable

As it possible to notice from the results reported in Table 15, in each of the four subsections of the questionnaire the elimination of poorly correlated items has led to an increase in the validity of the questionnaire. This proves the usefulness of eliminating the selected items, besides the advantages coming from a shorter questionnaire. In fact, by eliminating the selected items the number of questions is reduced from a total of 64 to a total of 56, with consequent benefits in terms of mental effort required to the individual and improvement in the reliability of the answers.

Considering now the interviewed populations as a variable in the statistical analysis of the survey results, it might be interesting to study how the results change depending on interviewed population. It was in fact mentioned that the target individuals belong mainly to three different categories, i.e. STELLANTIS worker with experience in collaborative automation, robotics and manufacturing processes college professors and finally MSc and PhD students.

The analysis is carried out by computing and comparing the answer means and the averages values of the standard deviations of the answers given depending on the interviewed population.

The results, reported in Table 16, show the mean value and the average standard deviation of the answers to the survey for each population per questionnaire section. The analysis shows that among the three different populations samples considered, Msc and PhD students are the ones that show more confidence in the possibility to make assembly task suitable for automation (answers mean value >0.60) By cross checking the mean values, it is possible to notice that ones showing the highest thrust in robot capabilities, for all the interviewed populations, are related to the feeding system characteristics and the HR communication, while as expected safety still remains a concerns for each individuals category.

Table 16 HR Task Allocation Survey: Population Analysis

Population Category	Part/Task Characteristics		HR communication requirements		Workstation Safety		Feeding System Features		AHP Matrix	
	M	SD	M	SD	M	SD	M	SD	M	SD
STELLANTIS Workers	0,49	0,22	0,56	0,21	0,45	0,18	058	0,21	NS	1,93
College Faculty Members	0,53	0,19	0,54	0,23	0,42	0,13	0,58	0,19	NS	3,2
MSc & PhD Students	0,64	0,22	0,67	0,17	0,55	0,15	0,62	0,20	NS	2,49

Concerning the data dispersion, it is worth mentioning that the safety section is the one showing the lower standard deviation, meaning that the importance of worker’s safety is something all the individuals subjected to the study agree at the same level.

Onn the contrary, the section related to part/task characteristics is the oen showing the highest dispersion. This can be explained by considering that those items can be answered taking into account the ergonomics and productivity of the workstation on one side, and the safety and well-being on the other, which may increase the indecisiveness levels and thus lead to more dispersed results.

In conclusion to this chapter, it is possible to state the first research questions presented in the introduction to this study has been partially answered. A new HR task allocation method which takes into account a larger scope of decision variables has been proposed and developed. The subjectivity that commonly affects this kind of studies has been partially reduced by approaching the evaluation problem by developing a questionnaire to be distributed to individuals experienced in collaborative robotics. By developing an extensive survey questionnaire tailored on assembly automation, gathering the evaluations of as many knowledgeable individuals as possible and statistically verify their reliability, the aim is to creat an objective method to effectively evaluate and verify the suitability of tasks for collaborative automation.

To further validate the proposed approach, a feasibility study will be presented and carried out in the next chapter. Assembly tasks belonging to real industrial scenarios provided by STELLANTIS SPA will be evaluated and distributed according to the proposed approach. The results will be implemented into a simulation environment (Tecn0matix Process Simulate) in order to carry out a feasibility study of the process.

Finally, through the software quantitative results concerning productivity, safety and ergonomics will be extracted and discuss to ultimately verify the applicability of the developed HR task allocation method.

CHAPTER FIVE

HR TASK ALLOCATION METHOD TESTING AND VALIDATION

The purpose of the present chapter is to verify the validity of the proposed task allocation method (Chapter four) by applying it to the assembly case scenario presented and described in the third chapter.

The methodology followed through this chapter (Fig.12) is to take each of the task and sub-task identified through the hierarchical task analysis (Table 2) and, after characterizing them through the defined describing criteria listed in the look-up tables, a final “automability score” is assigned to each of them.

The following step is to perform a first task distribution between the human and the robot according to the result of the tasks allocation objective function (Eq. 4.6) and the task sequence precedence defined through the HTA (Table 2).

Last step is to implement the collaborative scenario in Tecnomatix Process Simulate; through which quantitative results can be derived. A first accomplishment will be achieving a final task allocation procedure by considering the different tasks times and taking into account possible space constraints . Ultimately, the simulation will allow to achieve a station layout for the collaborative assembly cell, define paths for the mobile robot and carry out a productivity comparative analysis between the already simulated manual assembly scenario (Chapter 3) and the newly designed collaborative scenario.

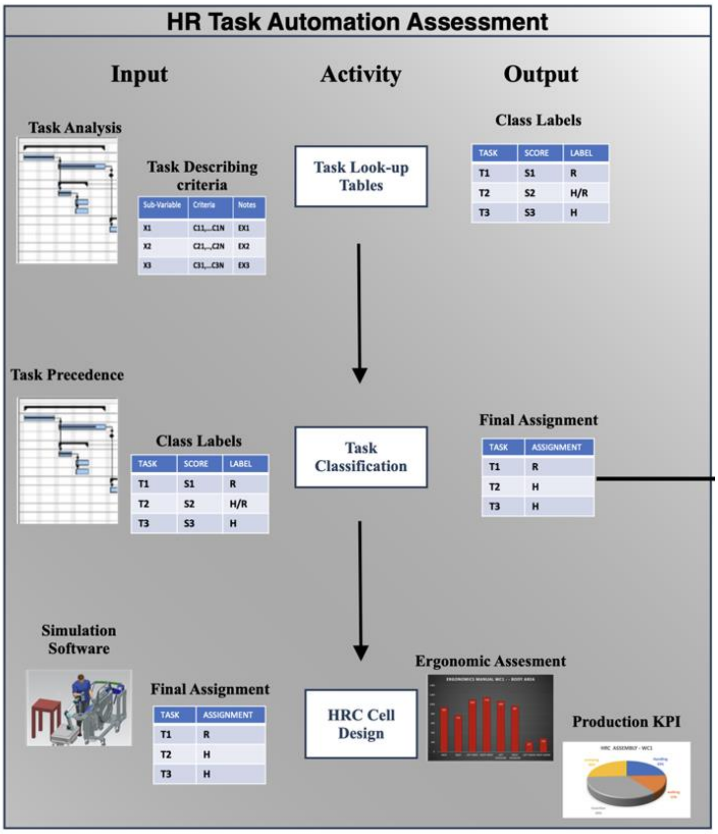


Figure 12 Digital Twin Supported Task Allocation in HRC

To verify and increase the robustness of the new HR task allocation method, this chapter will also present the case of a second assembly station, featuring different assembly components and tasks carried out manually.

Following the same procedure, the proposed task allocation method will be tested through the second assembly scenario in order to further verify the applicability of the proposed new approach.

Finally, the chapter will be closed by an overall analysis of the results coming from productivity comparative analysis of the redesigned collaborative workstation, while the safety and ergonomic validation will be dealt with in the following chapter.

5.1 HR Task evaluation and assignment through the proposed approach

As mentioned in the introduction for this chapter, the proposed task allocation method is applied to the assembly scenario under analysis by assigning scores to the characteristics of the tasks reported in Table 2 according to the describing criteria listed in the developed look-up tables.

The results of the scoring procedure are reported in Table 17; applying the proposed task allocation approach to the assembly activities leads to a task distribution in which both the robot and the worker play a significant role.

The logic followed for the HR task assignment is that the task resulting in a SCA (Suitability for Collaborative Automation, Eq. 4.) score lower than 0.4 are assigned to the worker, while the ones scoring a value of 0.6 or higher are assigned to the robot. To allow for a better flexibility in the task assignment process, the task with a SCA between 0.4 and 0.6 (labeled as H/R in Table 17) are regarded as equally suitable for human or robot. The final distribution will thus depend on other factor such as task completion time or task sequence precedence.

5.2 HRC Tasks Simulation Results

After performing the distribution of the assembly tasks between human and cobot, an analysis of the actual feasibility of the new process and its possible productivity improvement has been carried out by implementing the collaborative scenario into Tecnomatix Process Simulate.

Table 17 HR Task Allocation Result - Workstation 1

Task Name	Score	Resource	Notes
1.1 Pick Front glass door from the cart	0.33	Human	
1.2 Position front glass door on the cart	0.32	Human	
1.3 Push component against anterior door side	0.32	Human	
1.4 Pick scredriver from shelf	0,64	Robot	Robot picks the tool from the shelf, hand it to the worker and take it back.
1.5 Take one M12 screw from pouch	0.44	H/R	
1.6 Position the screw on tool tip	0.43	H/R	
1.7 Fix front glass door by screwing	0.27	Human	
1.8 Place screwdriver on shelf	0,64	Robot	Robot picks the tool from the shelf, hand it to the worker and take it back.
2.1 Pick coverage from cart	0.67	Robot	
2.2 Position coverage on the door frame	0.66	Robot	
2.3 Pick screwdriver from shelf	0.64	H/R	Robot picks the tool from the shelf, hand it to the worker and take it back.
2.4 Take one M12 screw from pouch	0.44	H/R	
2.5 Position the screw on tool tip	0.43	H/R	
2.6 Fix coverage by screwing	0.43	H/R	
2.7 Place screwdriver on shelf	0.64	Robot	Robot picks the tool from the shelf, hand it to the worker and take it back.
3.1 Pick seal from assembly cart	0.67	Robot	
3.2 Position seal on door frame	0.38	Human	
3.3 Insert seal in the outer part of the door	0.32	Human	
3.4 Insert seal in the inner part of the door	0.32	Human	
3.5 Visually check the insertion	0.67	Robot	
3.1.1 Start inserting manually from the belt side	0.32	Human	
3.1.2 Continue manually the insertion to the other side	0.32	Human	
3.1.3 Insert the component from the rear area of the B pillar door by coupling it with the sheet metal flap	0.32	Human	
3.2.1 Go to the other side of the door	0.32	Human	
3.2.2 Apply the component placing it inside the duct	0.32	Human	

Task Name	Score	Resource	Notes
3.2.3 Arrange it up to the B pillar using manual pressure	0.32	Human	
4.1 Go to outer part of door	0.83	Robot	
4.2 Pick vertical coverage from assembly cart	0.85	Robot	
4.3 Position vertical coverage on door frame	0.81	Robot	
4.4 Apply force to insert joints in their slots	0.47	H/R	
4.5 Visually check the coverage insertion	0.67	Robot	
5.1 Pick belt from assembly cart	0.39	Human	
5.2 Insert the belt in on the sliding seat starting from the front door area	0.36	Human	
5.3 Manually insert the gasket into the groove	0.36	Human	
5.4 Using manual pressure slide the gasket up to the B pillar	0.36	Human	
5.5 Check the correct alignment	0.80	Robot	
6.1Pick mirror from assembly cart	0.62	Robot	
6.2 Insert connector	0.40	H/R	
6.3 Take the wire and insert its connector	0.39	Human	
6.4 Manually couple the mirror into the slot below	0.39	Human	

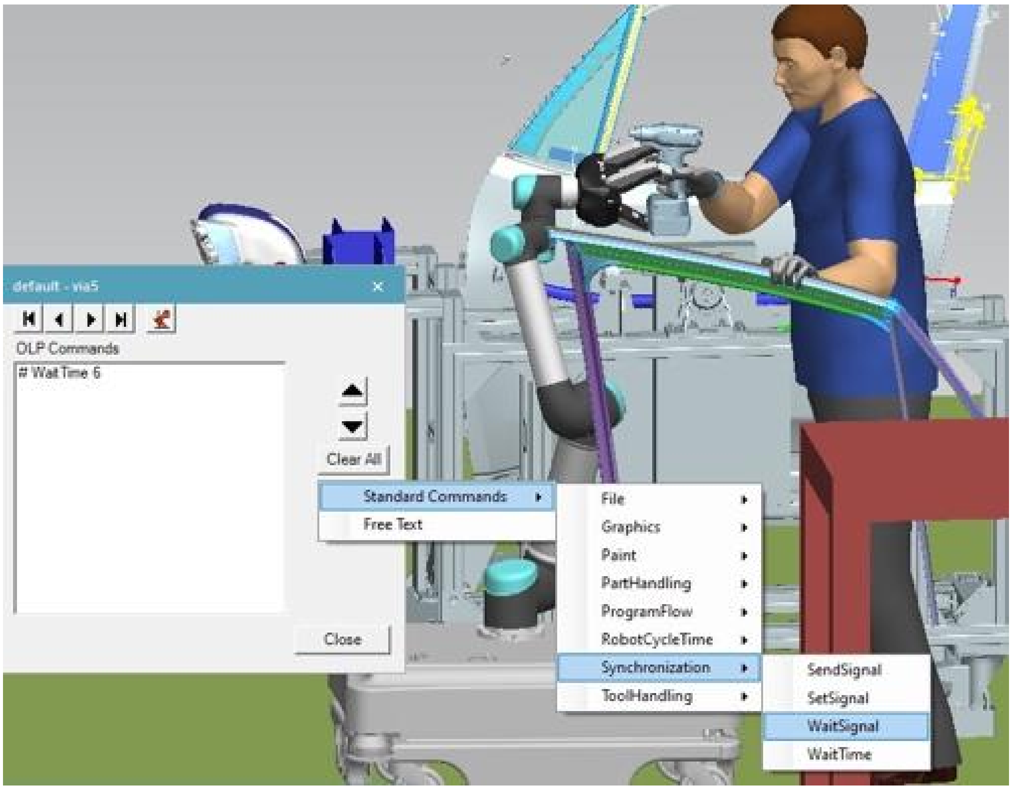
5.2.1 Digital Twin setup

As previously hinted, one of the novelties and main complexities of this study is the attempt to deploy an autonomous mobile robot (AMR) in a scenario of intensive collaboration, which necessitates a careful layout and activity synchronization planning. Thus, one of the reasons that makes the implementation into Process Simulate (PS) environment extremely useful is the possibility to design robot-path planning and time in a detailed way: through the design of object flow operation

(Fig.12) for each operation the path of the AMR is design by defining a set of location points. Furthermore, the synchronization of the activities is achieved through the teach pendant tool available in PS environment (Fig.13), which allows to write or define a set of OLP commands (wait, start, go) that can be triggered by defining manually waiting and running times ,or by embedding sensors in the cell layout that trigger robot's actions.

Since, as it was shown in Chapter 3, human activities must be entirely designed manually, and no data about human-robot interaction times are available, for the handover activities of tools or parts between human and robot a time of 4 seconds is allocated. This time is the result of rough estimation of the average of the possible interaction times according to the different technologies.

If for instance the technology used is a gesturer-based recognition [40], the processing timing will be close to fraction of seconds, as no action is required by the worker and everything is autonomously processed by the communication systems.

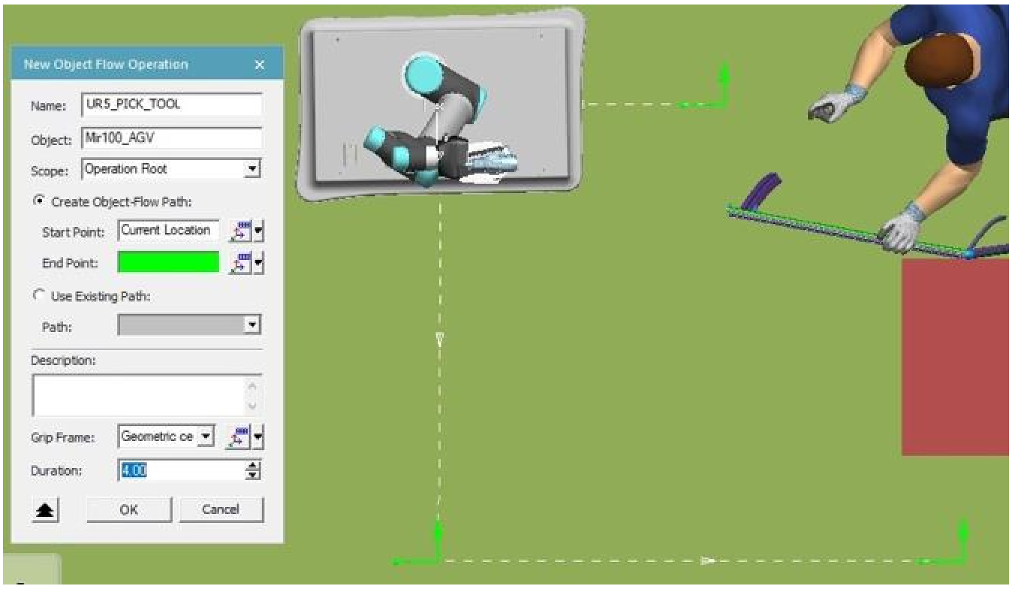


default - via5

OLP Commands

Wait Time 6

Figure 13 SImulation Robot OLP Programming



New Object Flow Operation

Name: UR5_PICK_TOOL

Object: Mr100_AGV

Scope: Operation Root

● Create Object-Flow Path:

Start Point: Current Location

End Point:

○ Use Existing Path:

Path:

Description:

Grip Frame: Geometric ce

Duration: 4.00

Figure 14 SImulation AMR Trajectory and Speed Design

On the other hand, if the technology used is speech recognition based [41], a protocol of successive commands shall be defined, thus increasing HR interaction time to 6-8 seconds.

5.2.2 HRC Task Allocation Results

After allocating time windows to account for the HR physical interactions and modify acceleration and speed of both the robotic manipulator and the AMR according to the standards [20][21](Chapter 6), performance indicators concerning the productivity of the cell have been extracted through Process Simulate.

For the productivity comparison analysis between the two assembly scenarios, the parameters used as means of comparison have been the cycle time and the walking distance for each assembly activity (Table 18).

To extract the cycle time through Process Simulate, a MTM report has been generated for each assembly activities, while for the walked distance it has been used an option embed in TBS which allows to generate a walking report which provides information about walking trajectories, distance, and number of steps.

In order to grant a comparison between the two case studies as reliable as possible, the digital twin for the collaborative assembly has been developed starting from the one previously designed for the manual process. This has been done by keeping the human activities simulated through the human TSB (Task Simulation Builder) and integrating them to the newly programmed robot operations.

Table 18 Productivity Comparative Analysis - Workstation 1

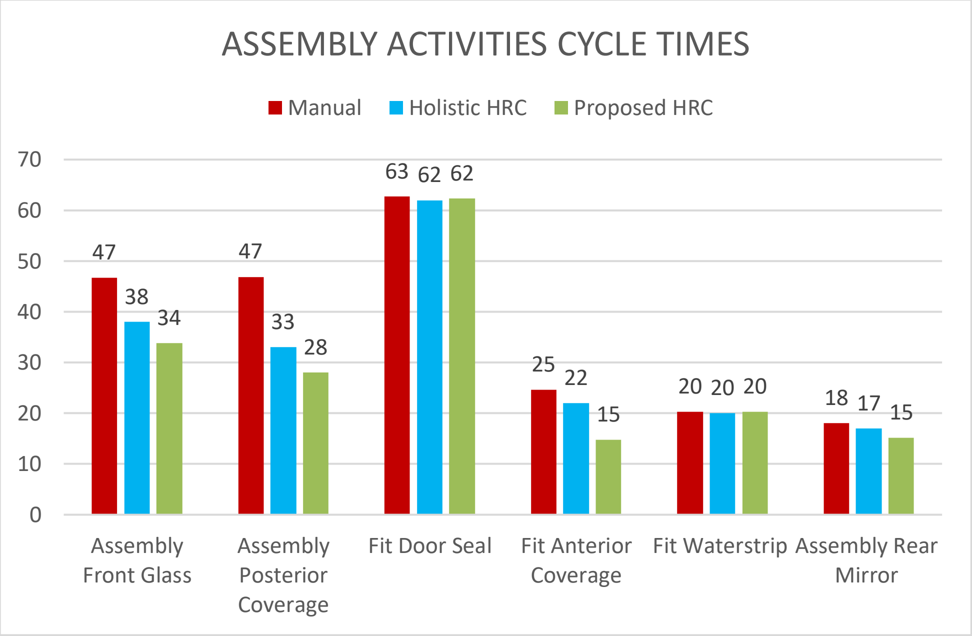
Activity Name	Cycle Time [s]			Walked Distance [m]	
Block wheels	12	12	12	6	6
Insertion front glass door	11	11	11	0	0
Screwing 1 front glass door	21	12	12	7	1
Screwing 2 front glass door	15	15	11	5	7
Insertion posterior vertical coverage	11	5	0	0	0
Screwing 1 posterior vertical coverage	10	8	8	2	1
Screwing 2&3 posterior vertical coverage	/	/	/	/	/
Place Screwdriver and get front door seal	14	14	14	0	0
Insertion front door seal	11	6	6	6	1
Fitting front door seal - External	4	4	4	0	0
Go around cart	34	34	34	1	1
Fit front door seal - Internal	24	24	24	1	1
Pick anterior vertical coverage	8	5	5	5	4
Inserting anterior vertical coverage	17	17	10	0	0
Pick and inserting glass water-strip	20	20	20	2	3
Pick rearview mirror	8	4	4	4	0
Inserting rearview mirror	13	13	11	2	2
Go around cart	5	5	5	4	5
Total	238	209	191	42	25
Efficiency Improvement [%]	/	12,2	19,7	/	40,5

A first conclusion that can be derived by looking at the task distribution is that, as expected, the robot is taking over mostly Non Value-Added Activities (NVAA), such as taking back and forth tools and components, thus avoiding handling times.

This is confirmed by the results reported in Table 18: the deployment of the collaborative robots allows for a significant reduction of the distance walked per cycle (40,5 % improvement). Supposing a working shift of 8 hours, this leads to an overall reduction of 2550 m (1,6 miles) supposing the same number of assemblies completed, with significant improvements in terms of productivity of the cell and physical energy expenditure of the worker.

Considering the activities cycle time, the positive trend already shown by the collaborative assembly scenario presented in Chapter 3, i.e. only NVAA are assigned to the robot, is confirmed and further improved by applying the proposed task allocation procedure (Fig.15)

Figure 15 Activities Cycle Times Comparison



As the case study under analysis does not involve significantly dangerous activities like welding or sawing, nor it involves the handling of particularly heavy components, that robot is found to take over some value-added yet simple assembly activities, with low requirements of dexterity and precision.

However, just by assigning to the cobot two more positioning activities, respectively handling and position of the anterior and posterior vertical coverages, a productivity efficiency improvement in comparison to the manual and first collaborative scenario, respectively of 8,6 % and 19,7 %, is achieved.

Again, supposing a work shift of 8 hours, this leads to an increase of 29 more assemblies completed per shift, going from 121 manually assembled doors to 150 HRC assemblies.

5.3 Task Allocation Method Testing – Second Case Study

For a further testing and validation, the new task allocation method has been verified through a second manufacturing case study.

In the next sub-chapters a breakdown analysis of the assembly activities will be carried out (sub-chapter 5.3.1), the results of the task distribution between worker and robot will be reported (sub-chapter 5.3.2) and finally a productivity comparative analysis between the manual and the collaborative assembly scenarios will be performed.

5.3.1 The assembly processes

The manufacturing scenario now considered is again belonging to the automotive final assembly. The methodology followed to analyze the new assembly process' features and requirement has been the same as for the first case (Sub-chapter 2.2.1). The assembly activities have been broken down in tasks and sub-tasks through the Hierarchical Task Analysis approach (Table 19); then the process requirements and the physical characteristics of the parts (Table 20) have been listed and finally resource choices have been made.

As it possible to see in Table 19, where all the tasks and sub-tasks identified through the HTA are listed, the new case study shows several similarities in terms of assembly tasks involved. However, as shown in Table 20 the second assembly process involves the assembly of four components, extremely different in shape, size, and texture. Differently from the first workstation, all the components are assembled on the same side of the door. Also, two different tools are used for the screwing operations necessary to fix the components, thus increasing the number of walking activities required due to the need to change tool.

Furthermore, as it has been done for the previous case study, an ergonomics evaluation of the body parts that subjected to the highest workload during the assembly cycle has been carried out by means of the assessment tools available in Process Simulate (Table 20)

Table 19 Assembly Components Properties – Workstation Three

Component /Tool Name	Weight [Kg]	Longest Diagonal [mm]	Flexibility Degree	Fragile Surfaces
Speaker	0,6	0,43	low	Yes
Door Panel	0,3	3,2	Low-medium	No
Window-Controls	0,3	0,17	low	No
Speaker Frame	0,2	0,06	medium	No
Power Screwdriver	0,2	1,1	low	No
SKILL Screwdriver	1,1	2,1	low	Yes

Table 20 HTA Manual Assembly Workstation 3

Super ordinates	Task Components, Operations and Plans	Notes
0	Assembly of the brake disc on the assembly station; Plan 0. Do 1, 2, 3, 4 and 5. Then exit. 1. Assemble the speaker on the door carrier 2. Assemble door panel on door carrier 3. Assemble window\-control panel on door panel 4. Assemble speaker frame on door panel 5. Raise door	
1	Assemble the speaker on the door panel; Plan 1. Do 1.1, 1.2,1.3, then 1.4, 1.5, 1.6 four times, then 1.7, and Exit 1.1 Go Pick speaker from cart 1.2 Position speaker on door panel 1.3 Go pick screwdriver from tool shelf 1.4 Pick M4 screw from pouch 1.5 Insert M4 screw on tool tip 1.6 Tighten M4 screw 1.7 Go place screwdriver on tool shelf	
2	Assemble door panel on door carrier, Plan 1. Do 2.1, 2.2, 2.3, then 2.4, 2.5 and 2.6 two times, then 2.7 and then exit. 2.1 Take door panel from the cart 2.2 Fit door panel on door carrier 2.3 Go pick screwdriver from tool shelf 2.4 Take one M4 screw from pouch 2.5 Position M4 screw on tool tip 2.6 Tighten M4 screw on door panel 2.7 Go put screwdriver on tool shelf Fit door panel on door carrier. Plan 2.2. Do 2.2.1, 2.2.2, 2.2.3. Then Exit	
2.2	2.2.1 Tilt the panel over the door frame	

Super ordinates	Task Components, Operations and Plans	Notes
	2.2.2 Hook the superior part of the door panel on the door frame using both hands 2.2.3 Insert the lower part of the door panel by applying a push force	
3	Assemble the window-control panel on the door panel. Plan 3. Do 3.1, 3.2, 3.3, 3.4 and 3.5. Then exit 3.1 Take the two parts of the component from the cart 3.2 Manually join the two parts of the component 3.3 Hook the component on the slot on the door panel by pushing it 3.4 Go pick the screwdriver from the tool shelf 3.5 Pick one M4 screw from the pouch 3.6 Fix M4 screw on the tool tip 3.7 Tighten the screw to fixate the component 3.8 Put the screwdriver back on the tool shelf	
4	Assemble speaker frame on the door panel. Plan 4. Do 4.1, 4.2, 4.3 4.4, then 4.5 and exit 4.1 pick up the speaker frame from the cart 4.2 Manually position the speaker frame in its seat on the door panel 4.3 Apply manual pressure to insert the centering pin 4.4 Apply manual pressure to insert to trigger the # 8 pinetti	
5	Raise door. Plan 5. Do 5.1, 5.2, 5.3 5.4. Then exit 5.1 Take SKILL driver from tool shelf 5.2 Insert the tip of the tool into the lifting/lowering mechanism 5.3 Raise door 5.4 Put the SKILL driver back on the shelf	

Table 21 Manual Assembly Time percentages per posture categories – Case Study #2

		Assembly Speaker		Insertion Doorpanel		Fixing DoorPanel		Assembly Windowcontrol		Assembly Speakerframe		Raise Door	
		M	H	M	H	M	H	M	H	M	H	M	H
Neck	Flection	3	70	32	44	8	58	13	49	7	59	1	68
	Extension	0	0	0	0	0	0	0	0	0	0	0	0
	Rotation	33	23	57	3	32	34	23	31	44	0	62	6
	Lat. Bend	33	7	34	0	48	8	36	5	6	0	8	0
Back	Flection	11	0	46	0	15	2	10	0	5	0	0	0
	Extension	0	0	0	0	0	0	0	0	0	0	0	0
	Axial twist	13	0	5	0	16	0	1	0	5	0	0	0
	Lat. Bend	11	0	19	0	13	0	5	0	1	0	0	0
Right Wrist	Flection	6	2	21	24	22	4	17	12	2	0	3	65
	Extension	33	23	9	25	22	23	20	7	6	75	23	0
	Sup/Pron	18	4	43	7	23	6	18	20	38	40	2	67
	Ulnar/Rad	17	44	29	24	22	29	15	34	4	66	3	85
Left Wrist	Flection	28	18	60	23	25	14	27	21	0	0	7	0
	Extension	23	3	0	0	23	1	9	6	21	62	61	0
	Sup/Pron	18	1	7	28	21	6	26	17	25	52	1	59
	Ulnar/Rad	16	33	21	30	17	32	27	12	13	29	3	60
Right Shoulder	Flection	46	11	49	6	59	14	34	23	17	0	2	0
	Extension	56	8	37	1	62	9	35	26	16	0	6	0
	Abduction	2	0	18	20	3	0	3	0	22	0	0	0
	Rotation	13	1	0	0	18	0	8	0	0	0	0	0
Left Shoulder	Flection	0	0	6	20	0	0	0	0	0	0	0	0
	Extension	36	12	35	4	46	14	10	45	54	28	25	1
	Abduction	2	0	30	0	15	0	2	0	20	0	0	0
	Rotation	7	10	6	0	20	3	12	0	0	0	1	0
L Elbow	Flection	0	0	32	0	0	0	5	0	0	0	0	0
R Elbow	Flection	43	11	16	5	35	18	31	4	64	18	9	60

Due to the just above-mentioned reasons this station appears to present more challenges in comparison to the first examined workstation. In the following sub chapter the new task allocation method proposed in this research will be applied to tasks listed in Table 20 and the results of the preliminary HRC task distribution will be presented and discussed

5.3.2 HR Task Allocation Results Analysis

The application of the proposed task allocation method to the set of tasks listed in Table 20 results in the preliminary HR task distribution listed in Table 22. Differently from the previous assembly scenario, in this case the evaluation of the tasks through the developed look-up tables assigns to the cobot only simple handling operations of taking and bringing tools back and forth.

However, as already hinted the current scenario presents more challenges for collaborative automation if compared to the first assembly process examined. Although the components to be handled are fewer (four instead of six), their shape and size are less suitable for robot handling (Table 1; Table 19). For instance, from a first brief analysis the insertion of the speaker frame into its pin slots and the joining of the two window-control panel requires a high degree of human tactfulness and the application of an insertion force, the door panel is excessively bulky to be handled by the robot and the control-panel location is in a location difficult to reach.

Furthermore, differently from the first scenario this time all the components to be manipulated are to be assembled on the same side of the door; this poses a significant job distribution constraint, as both robot's and worker's motions are constrained in a limited space volume.

Then, it appears quite logical that in this context the actions permissible for the robot are constrained to simply carrying tools back and forth, as the significantly reduced inter-operational distance would not allow it to safely operate alongside the worker.

It can thus be stated that the test by means of the virtual simulation proves once again the validity of the proposed task allocation method for designing human-robot collaborative assembly work-stations; two different assembly scenarios of different levels of expected suitability for automation lead, by applying the new task allocation method, to a scenario of more intensive collaboration (first case) and one that does not appear to benefit from the deployment of a collaborative robot.

The strength of the virtual testing carried out relies on the fact that, differently from most of the existing research, the sets of assembly tasks used to prove the validity of the new method presented by this study has been derived from the analysis of a real manufacturing scenario, whereas most of the studies design a set of tasks tailored on the kind of related research.

In order to investigate more in depth the effects of the hypothesized approach, the following sub-chapter will present and discuss the results regarding productivity KPIs through a comparative analysis between the different scenarios that have been developed.

Table 22 HR Task Allocation Results – Test Case #2

Task Components, Operations and Plans	Score	Resource	Notes
1.1 Go Pick speaker from cart	0.60	H/R	Assigned to H. as per task precedence
1.2 Position speaker on door panel	0.52	H/R	Assigned to H. as per task precedence
1.3 Go pick screwdriver from tool shelf	0.77	Robot	R. hand tool to H; 4s time allocated
1.4 Pick M4 screw from pouch	0.47	H/R	Assigned to H. due to high precision requirements
1.5 Insert M4 screw on tool tip	0.46	H/R	Assigned to H. due to high precision requirements
1.6 Tighten M4 screw	0.27	H/R	Assigned to H. due to high precision requirements
1.7 Go place screwdriver on tool shelf	0.77	Robot	H. hand tool to R; 4s time allocated
2.1 Take door panel from the cart	0.29	Human	
2.2 Fit door panel on door carrier	0.28	Human	
2.3 Go pick screwdriver from tool shelf	0.77	Robot	R. hand tool to H; 4s time allocated
2.4 Take one M4 screw from pouch	0.47	H/R	Assigned to H. due to high precision requirements
2.5 Position M4 screw on tool tip	0.46	H/R	Assigned to H. due to high precision requirements
2.6 Tighten M4 screw on door panel	0.27	H/R	Assigned to H. due to high precision requirements
2.7 Go put screwdriver on tool shelf	0.77	Robot	H. hand tool to R; 4s time allocated
2.2.1 Tilt the panel over the door frame	0,39	Human	
2.2.2 Hook the superior part of the door panel on the door frame using both hands	0,31	Human	
2.2.3 Insert the lower part of the door panel by applying a push force	0,28	Human	
3.1 Take the two parts of the component from the cart	0.52	H/R	
3.2 Manually join the two parts of the component	0.37	Human	
3.3 Hook the component on the slot on the door panel by pushing it	0.28	Human	
3.4 Go pick the screwdriver from the tool shelf	0.77	Robot	R. hand tool to H; 4s time allocated

Task Components, Operations and Plans	Score	Resource	Notes
3.5 Pick one M4 screw from the pouch	0.47	H/R	Assigned to H. due to high precision requirements
3.6 Fix M4 screw on the tool tip	0.46	H/R	Assigned to H. due to high precision requirements
3.7 Tighten the screw to fixate the component	0.27	H	Assigned to H. due to high precision requirements
3.8 Put the screwdriver back on the tool shelf	0.77	Robot	H. hand tool to R; 4s time allocated
4.1 pick up the speaker frame from the cart	0.60	H/R	Assigned to H. as per task precedence
4.2 Manually position the speaker frame in its seat on the door panel	0.47	H/R	Assigned to H. as per task precedence
4.3 Apply manual pressure to insert the centering pin	0.37	Human	
4.4 Apply manual pressure to insert to trigger the # 8 pinetti	0.37	Human	
5.1 Take SKILL driver from tool shelf	0.92	Robot	R. hand tool to H; 4s time allocated
5.2 Insert the tip of the tool into the lifting/lowering mechanism	0.41	H/R	
5.3 Raise door	0.28	Human	Assign to H. as per narrow reaching location
5.4 Put the SKILL driver back on the shelf	0.92	Robot	H. hand tool to R; 4s time allocated

5.3.3 Productivity Comparative Analysis – Test Case # 2

Using the same approach followed for the first tested assembly scenario, thanks to the tools available in Process Simulate, productivity KPIs (Key Production Indicators) data have been extracted in order to carry out a comparative analysis between the manual process and the collaborative one (Table 22).

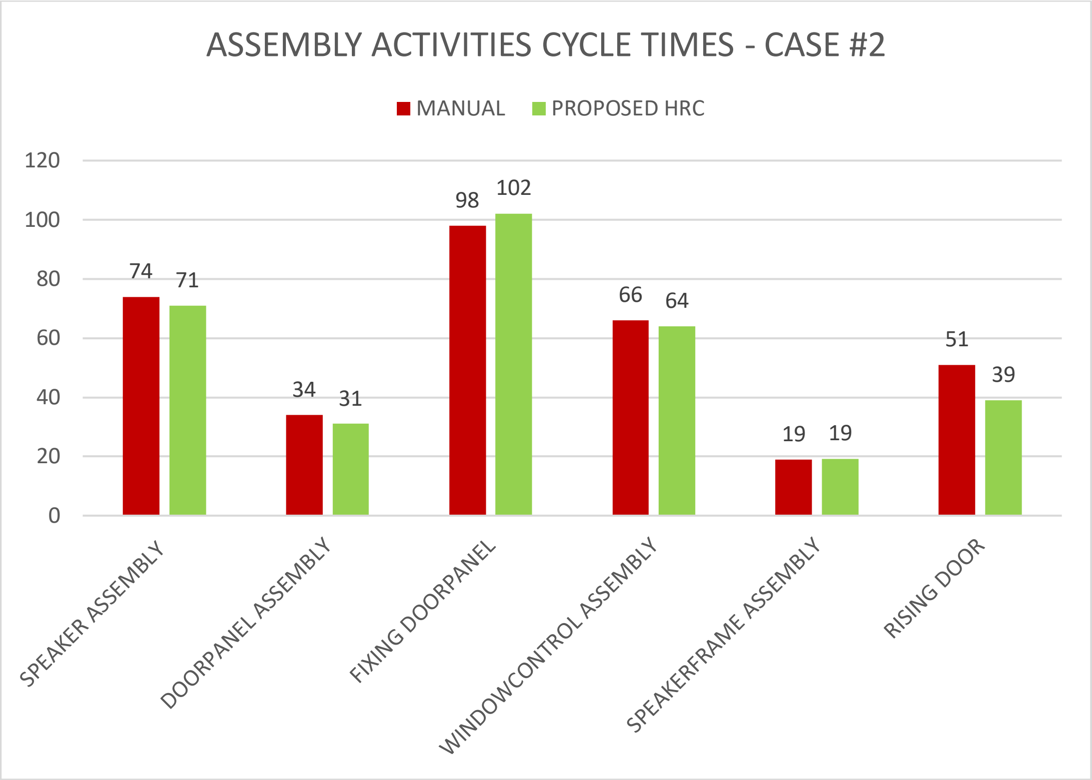
Table 23 Productivity KPI Comparative Analysis - Workstation Three

Activity Name	Cycle Time [s]		Walked Distance [m]	
	Manual	HRC	Manual	HRC
Assemble Speaker	72	73	11	7
Fit Door panel	33	32	2	2
Fixate Door Panel	98	104	15	10
Assemble Window-Control	66	61	16	7
Assemble Speaker Frame	19	19	4	4
Raise Door	34	30	8	5
Go around the cart and position tool	13	5	10	5
Total	335	324	66	40
Efficiency Improvement [%]	3,3%			33%

Unlike the first case study, this second scenario shows that the deployment of the collaborative robot does not lead to any significant improvement. As expected, more constrained conditions and less robot manipulation-friendly components makes it more difficult to effectively assign tasks to the robot.

The results of the proposed task allocation approach confirms this expected trend by assigning to the robot only simple back and forth operations.
However, no significant cycle time improvement is achieved (Fig. 15): this is explained by considering that the time saved by assigning walking activities to the robot is shadowed by the idle times of the HR interactions.

Figure 16 Assembly Activities Cycle Times Comparison - Case Study #2



The significant difference between the two real test cases used relies in the capability of the robot, in the first case, to carry out assembly activities that do not require any HR interaction, beside the worker sending the input command to the robot. It can thus be stated that through the use of the digital twin the fourth research question presented in the introduction to this research, i.e. whether it could be possible to validate a new task allocation logic through a digital twin, ahs been answered. By means of the developed virtual scenarios the proposed HRC distribution logic has been implemented and the feasibility of human-robot collaborative tasks have been checked. The simulation also allowed to derive some quantitative data concerning the walking times reduction and the changes in the activities cycle times.

Hence, from an operational time-span point of view, it has also been proved the validity of the new HR task classification method developed throughout this research, which confirms the expectations resulting from the preliminary analyses of the case studies and allocates tasks to human and robot in a feasible way.

The just presented chapter thus provided an answer to the fourth research question, while improving the answers to the first three. A final answer will be then provided in the following chapter, where the validity and the applicability of the proposed approach will be further proved through a safety and ergonomic validation of the redesigned process.

CHAPTER SIX

SAFETY AND ERGONOMIC ANALYSIS

Among all the requirements that a new design of a production process shall meet, before being implemented in the reality, the one that stands above all is that the safety of the worker must be granted at any instance according to the prescriptions of the existing standards. In this scenario, the main issue to be addressed in the hazard analysis and risk assessment, which will be developed in the next sub-chapters, is the presence of a mobile robot that follows the worker during the whole production cycle, which represents a strong step forward in the field of collaborative automation with respect to the existing solutions.

The novelty of a robot-partner actively performing assembly task and physically interacting with the worker represents a challenge in terms of compliance with legislative framework, as even the latest standards, the most notable being the ISO 15066, shows themselves to be too general [22] or sometimes even not effective [24]. Because of the complexity of this safety assessment, in this research the problem has been broken down into two different steps. In the first one the risk assessment is performed considering the robotic manipulator and the gripper attached to it, as it was standstill while performing a collaborative task. Second step will be to grant the safety of the worker by considering the mobile robot on which the manipulator is mounted.

6.1.1 Hazard analysis and risk assessment

As already mentioned, the first step in order to ensure that the designed collaborative assembly workstation meets the essential safety requirements is to perform a systematic hazard analysis and risk assessment.

To ensure the correctness of the assessment, to identify the possible hazards coming from the deployment of a cobot this study will refer to the Standard ISO 10218-2:2011 [19], which specifies the safety requirements for the integration of industrial robots and robots cell. This part of ISO 10218 describes the basic hazardous situations related to the use of industrial robots, describing also the requirements to eliminate or adequately reduce the risks associated to these hazards. It should be pointed out that this study will not consider the hazards specifically related to the process, but it is limited to the robot-related ones.

The standards provide a list of possible hazards specifying type or group of hazard (e.g. Mechanical, electrical, environmental etch …), origin of the hazard and potential consequences. The mentioned Table is provided I the annex (Table A.3.).

Considering that the robot is used mostly as a manipulator, and the process does not involve any welding or laser cutting operation, it is foreseeable that most of the identified hazards will be Mechanical ones (i.e. impacts, crushings, entanglements). As a result, the list of the hazards identified through the risk assessment is reported in Table 25 together with the collaborative mode embedded in the robot for the operation according to the Standard ISO15066:

Table 24 List of identified hazards

Hazard no	Hazard Name	Hazard Type	Type of contact	Safety Method
1	Impact with UR5 arm while handling part/tool	Mechanical	Transient	PFL
2	Impact with UR5 arm while AMR approach	Mechanical	Transient	SSM
3	Impact with 3F gripper while AMR approach	Mechanical	Transient	SSM
4	Impact with 3F gripper while handling tool/part	Mechanical	Transient	PFL
5	Impact with handled tool/part	Mechanical	Transient	PFL
6	Crushing between UR5 arm and door station	Mechanical	Quasi-Static	PFL
7	Crushing between 3F gripper and door station	Mechanical	Quasi-Static	PFL
8	Crushing between part/tool and door station	Mechanical	Quasi-Static	PFL
9	Trapping of fingers in gripper	Mechanical	Quasi-Static	PFL
10	Entanglement with clothe/hair	Mechanical	N/A	PFL
11	Friction with part/tool	Mechanical	N/A	PFL
12	Robot/operator Cutting with tool: screwdriver	Mechanical	Transient	PFL
13	Robot/Operator Puncture with tool: screwdriver	Mechanical	Transient	PFL
14	Unintended release of part/tool handled	Mechanical Economic	Transient	PFL
15	Poorly designed HR enabling device	Ergonomic	N/A	PFL
16	Poorly positioned HRI device	Ergonomic	N/A	PFL
17	Intrusion of non-authorized persons in the HRI zone	Mechanical	N/A	SSM
18	Impact during transition between PFL and HG	Mechanical	Transient	HG-PFL

The performed risk assessment identified a total of 17 hazards caused by the deployment of the collaborative robot, which as foreseeable are mostly belonging to the category of mechanical hazards.

The specification of the of the type of contact comes from the prescriptions of the standard ISO 15066, which states a difference in the force and velocity the robot is allowed to exert depending on whether the impact is transient (i.e. the worker is not trapped between the robot and another obstacle) and a quasi-static contact (i.e. The worker remains trapped between the robot links and another obstacle).

As already hinted in the introduction, the novelty of this standard with respect to the ISO 10218 1-2 [18] [19] is that it is the first standard prescribing specific limits of force, pressure and speed for the robot depending on different scenarios, defining the four different safety operating methods and how to mathematically evaluate limit force and speed.

More specifically the standard defines 48 body areas, to which are associated thresholds in terms of Force, Pressure and Transferred Energy (Tables A.4.; A.5), stating that the thresholds for a quasi-static impact are halved with respect to the transient ones.

In terms of ways to effectively eliminate or adequately reduce the identified hazards related to the robotic manipulator, the parameters or primary importance are the Force and Speed exerted by the robot while working close to the human worker.

According to the ISO 15066, the limits in terms of force and pressure shall be derived from the Table in the annex (Table A.4), depending on whether the comntact is quasi static or transient. To evaluate the pressure the standard specifies that the smallest area of contact between the interested body area and the impacting robot surface should be the one used for the evaluation.

To evaluate the limit velocity (relative between cobot and worker) the standard prescribe two possible way to compute the maximum allowed speed of the TCP.

The first way is to compute the transferred kinetic energy (Eq. 6.1) and compare it to the maximum allowed transferred kinetic energy according to Table A.5 , while the second way is by considering the maximum allowed pressure (Table A.4) depending on the area of contact (Eq. 6.2).

$$E_K = \frac{1}{2}\mu v_{rel}^2 \tag{6. 1}$$

$$v_{rel,max} = \frac{F_{max}}{\sqrt{\mu k}} = \frac{p_{max}A}{\sqrt{\mu k}} \tag{6. 2}$$

Where:

- v_{rel} is the relative velocity between the robot and the human body region
- μ is the reduced mass of the two-body system, expressed by Eq. 6.3:

$$\mu = \left(\frac{1}{m_H} + \frac{1}{m_R}\right)^{-1} \tag{6. 3}$$

Where:

- m_H is the effective mass of the body region (Table A.)
- m_R is the effective mass of the robot as expressed by Eq. 6.4

$$m_R = \frac{M}{2} + m_L \tag{6. 4}$$

- m_L is the effective payload including tooling and workpiece
- M is the total mass of moving parts of the robot

To evaluate the total mass of the moving parts of the robot, the ISO 15066 provides a simplified kinematic model the robot manipulator and of the links that shall be considered (Fig), provided along with a schematic representation of the cobot adopted for this study

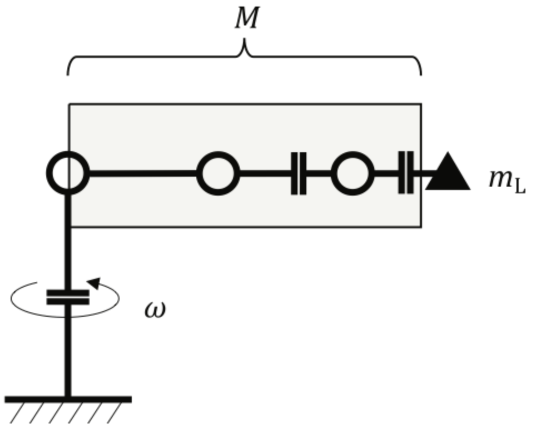


Figure 17 ISO15066 Mass Distribution Model

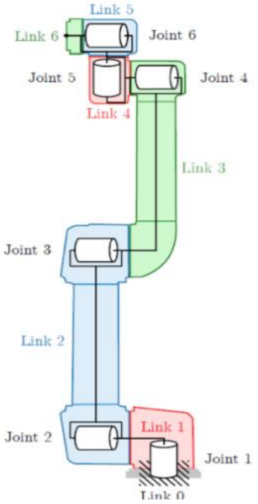


Figure 18 UR5 Schematics

For the evaluation of the robot moving mass for this study the masses of the links from the "elbow" to end effector (i.e. links #3-6) are considered.

The moving mass is evaluated for each assembly activity, as different workpieces lead to different values (Table 1). The values of kinetic energy, pressure and force exerted in normal operating conditions, according to the involved body region, are computed and analyzed.

The parameters primarily necessary to carry out the above-mentioned analysis are listed in Table 25.

Table 25 Technological Parameters For Risk Assessment

Technological resource	Parameter	Value
UR5 Robot	μ - Minimum	4,8 [kg] (Gripper Only)
	μ - Maximum	6 [kg] (Holding Screwdriver)
	TCP Speed – Normal	2000 [mm/s]
	TCP Speed – Reduced	750 mm/s
	Force – Normal	250 [N]
	Force – reduced	100 [N]
	Impact Area (Gripper + Wrist)	252 [cm2]
3F - Gripper	Mass	2,3 [kg]
	Force – Maximum	110 [N]
	Force – Minimum	30 [N]
	Closing Speed - Maximum	110 [mm/s]
	Closing Speed – Minimum	22 [mm/s]
	Area (Fingertip)	7,75 [cm2]

Next step of the process to perform a hazard analysis and risk assessment is to quantify and assign score to the risks associated to each activity. This is done by considering in a systematic procedure relevant factor such as how much the limit imposed by the ISO 1506 is overcome or how likely the hazard could occur.

The evaluation methodology used for the risk assessment is based on Pilz Criteria [42]. A score can be associated to each risk by performing an evaluation of the factors of Degree of Possible Harm (DPH). Probability of Occurrence (PO), Possibility of Avoidance (PA) and Frequency and/or duration of Exposure (FE).
A Pilz hazard rating has been calculated for the risk related with each hazard according to the formula:

$$PHR = DPH\ X\ PO\ X\ PA\ X\ PE \tag{6. 5}$$

The value attributed to each factor in Eq. is given referring to Table A. and choice is based on experience and on data coming from the simulations. Through the Pilza criteria is possible to assign a final score for the identified hazard and categorize it according to the following final values of the Pilz Hazard Rating (PHR): Negligible risk (PHR 1-10), Very Low Risk (PHR 11-20), Low risk (PHR 21-45), Significant Risk (PHR 46-160), High risk (161-500) and very high risk.

The categorization of the hazards allows to list them according to their priority and to ultimately eliminate the hazard source or reduce it to acceptable levels.
The results of the analysis, considering the risk associated to each assembly activity and the body regions possibly involved, are reported in Table 14 .

The results reported in Table 27 show that while some activities do not carry any additional risk, either because the robot does not play an active role in those activities or the two resources are separated in the space, other do present a low or significant risk for the operator.

Table 26 Pilz Risk Evaluation

Activity	Hazard No	Involved Body Parts	Limiting Factors	PHR	Risk category
Insertion front glassdoor	2-3	Abdomen, Pelvis,	Kinetic Energy AMR Speed	125	Significant Risk
Screwing 1 front Glassdoor	1; 4-9; 11-14.	Abdomen, Pelvis, Forearms,	Force; TCP Speed (UR5)	75	Significant Risk
Screwing 2 front glassdoor	No Hazards Identified	Abdomen, Pelvis, Forearms, Legs	N/A	N/A	N/A
Insertion Post Vert. Coverage	1; 4-8; 11; 14	Abdomen, Pelvis, Forearms, Legs	Force; TCP speed, (UR5)	25	Low Risk
Screwing 1 Post. Vert Coverage	1; 4-9.	Abdomen, Pelvis, Forearms, Legs	TCP Speed (UR5)		
Screwing 2&3 Post. Vert. Cov.	No Hazards Identified	N/A	N/A	N/A	N/A
Pick & Fitting Doorseal - front	1; 4-9; 11-14.	Abdomen, Pelvis, Forearms, Legs	Force, TCP Speed (UR5)	75	Significant Risk
Fitting Doorseal - rear	No Hazards Identified	N/A	N/A	N/A	N/A
Insertion Ant. Vert. Coverage	1; 4-8; 11; 14	Abdomen, Pelvis, Forearms, Legs	TCP Speed	12,5	Very Low Risk
Fitting Door waterstrip	No hazards Identified	N/A	N/A	N/A	
Insertion rearview Mirror	1; 4-8; 11; 14	Abdomen, Pelvis, Forearms, Legs	AMR speed Switch PFL→HG	75	Significant risk

Thus, the risk shall be reduced for those activities whose PHR is above the threshold of negligible risk (PHR = 10). The most effective way to achieve this reduction is to act on the DPH factor, as it is the one most directly related to the robot itself, while the other three factors would also require changes in the process design.

In order to effectively reduce the degree of possible harm it is necessary to refer to the evaluation (according to the ISO 15066) of speed, force and pressure exerted by the robot during each operation (Table 14, column 4).

The result of the evaluation is that in most of the task the force exerted by the manipulator in normal operation mode (250 N) is higher than the pain threshold of the body regions involved (Table A.3). Furthermore, the normal operation speed of the robot often leads to values of energy transferred above the limits prescribed (Table A.4).

Thus, to reduce the risks under acceptable levels, it is decided to operate the robot in the “reduced mode” that can be selected through the manipulator’s controller. This operating mode allows for the robot to be operated exerting a maximum force of 100 N (which does not affect negatively the process as the parts to be handle are of limited weight) and at a TCP speed of 750 mm/s.

Actually the result of the evaluations carried out according to the ISO 15066 showed that the robot can exert a force of 220 N and a maximum speed of 860 mm/s without overcoming the thresholds prescribed by the standard.

However, as shown by [22][24] the ISO 15066, despite being more specific, still presents some defects and, as proven especially by [24] by studying the effect of a gripper pinching a human hand, significant damages can be done to skin and bones even if formally the process complies with the standards.

For these reasons and because of the strong degree of collaboration enabled by this study, the decision is to keep the robot parameters well below the acceptable limits.

Thus, to show how these changes might affect the assembly of the cell, and how it is possible to take them into account in the early stages of design, the next sub-chapter will show how and to what degree is possible to make a digital twin compliant with the safety standards using the tools available in the software.

6.1.2 Digital twin compliance with ISO 15066

As shown in the previous sub-chapter, the results of the hazard analysis and risk assessment showed that the parameters that require changes in order to be compliant with the ISO 15066 are the TCP speed and force of the collaborative manipulator (Power and force limited safety mode) and the speed of the autonomous mobile robot (Speed and Separation Monitoring safety mode).

While it is not possible to make any modification to the force exerted by the robot in the virtual simulation, it is indeed possible to effectively act on the speed and kinematics of the robots to grant the safety of the workers.

Regarding the former, it is possible to act in two different ways depending on the resource considered; to modify the speed of the mobile robot it is possible to act on the 'Object flow operations tool" already showed in Fig. 13. By means of this tool different flow su-operations have been defined for the AMR, each featuring a speed related to the distance of the AMR from the operator. To satisfy this necessity, Process Simulate allow to define a dynamic distance between objects in the simulation (in this case the worker and the mobile robot); this dynamic distance is thus monitored so that the AMR is allowed to operate at maximum speed when it is far from the worker, while it reduces its speed and eventually stops when approaching the human operator.

To evaluate the safety distances between human and robot, and define operating zones (namely safe zone, warning zone and danger zone), the deployment of a common monitoring device called “SafetyEye” has been assumed, whose functioning and evaluation algorithms implemented in this study are explained in detail in [32].

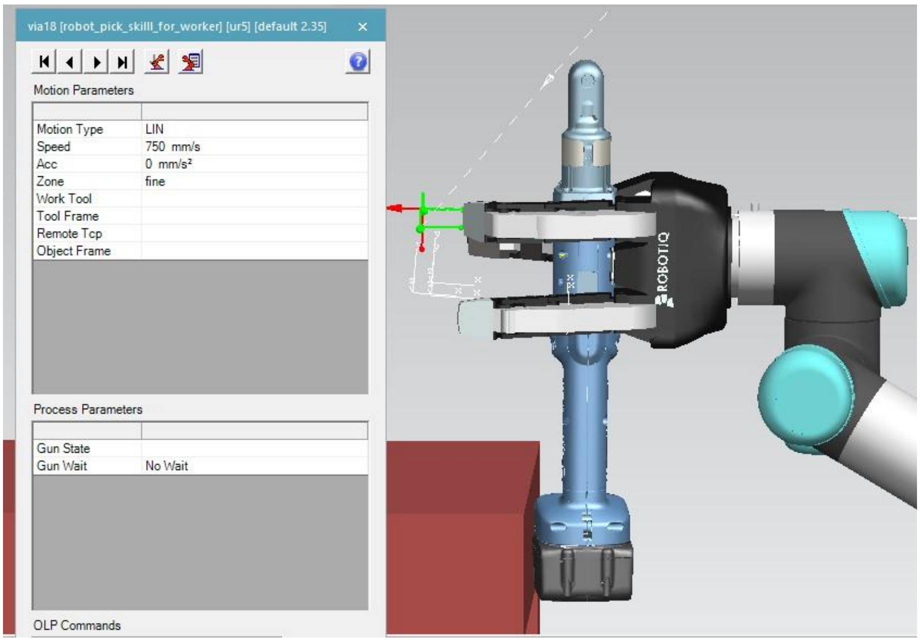
The second resource that needs to be monitored, in order to ensure that any possible impact between the robot and the worker falls below the prescribed thresholds, is the collaborative manipulator mounted on the AMR.

To act on the robotic manipulator’s technical parameters, a tool is used in process simulate called “Teach Pendant”(Fig. 19), which is the virtual equivalent of the device used in real manufacturing scenarios to control industrial robots.

Through this tool robot’s speed and accelerations have been modified for each operation according to safety limits computed using the prescriptions of ISO 15066 (Table 27).

Finally, to reduce the risk levels computed through the Pilz criteria, the probability of Occurance (PO) has been reduced for the robotic manipulation operations the end-effector paths through Process Simulate “Path Editor” feature (Fig.20). To design movements and path locations for the robot studies analyzing how to design and deploy seamless human-robot handovers [43][44] have been considered and applied to the developed assembly scenario. Adopting the corrective measure presented in this chapter, it is thus possible to develop an accurate process and spatial layouts in the early stages of design. This allows to derive more reliable results regarding activities cycle times.

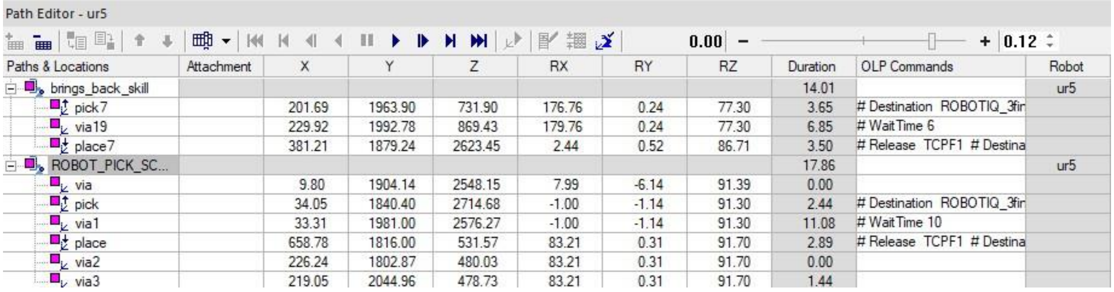
Figure 19 Process Simulate - Robot Teach Pendant



Motion Type	LIN
Speed	750 mm/s
Acc	0 mm/s²
Zone	fine
Work Tool	
Tool Frame	
Remote Tcp	
Object Frame	

Gun State	
Gun Wait	No Wait

Figure 20 Process Simulate - Robot Path Editor



Paths & Locations	Attachment	X	Y	Z	RX	RY	RZ	Duration	OLP Commands	Robot
brings_back_skill								14.01		ur5
pick7		201.69	1963.90	731.90	176.76	0.24	77.30	3.65	# Destination ROBOTIQ_3fir	
via19		229.92	1992.78	869.43	179.76	0.24	77.30	6.85	# WaitTime 6	
place7		381.21	1879.24	2623.45	2.44	0.52	86.71	3.50	# Release TCPF1 # Destina	
ROBOT_PICK_SC...								17.86		ur5
via		9.80	1904.14	2548.15	7.99	-6.14	91.39	0.00		
pick		34.05	1840.40	2714.68	-1.00	-1.14	91.30	2.44	# Destination ROBOTIQ_3fir	
via1		33.31	1981.00	2576.27	-1.00	-1.14	91.30	11.08	# WaitTime 10	
place		658.78	1816.00	531.57	83.21	0.31	91.70	2.89	# Release TCPF1 # Destina	
via2		226.24	1802.87	480.03	83.21	0.31	91.70	0.00		
via3		219.05	2044.96	478.73	83.21	0.31	91.70	1.44		

To complete the analysis of the results achieved by testing the proposed task allocation method through a real case assembly process, the next sub-chapter will present and discuss the results of ergonomic comparative analysis between the manual process and the collaborative assembly.

6.2 Ergonomics assessment comparative analysis

One of the research questions raised in the introduction to this study concerns the possibility to include an evaluation of the physical workload on the worker in the enlarged scope of parameters considered in the proposed task classification logic.

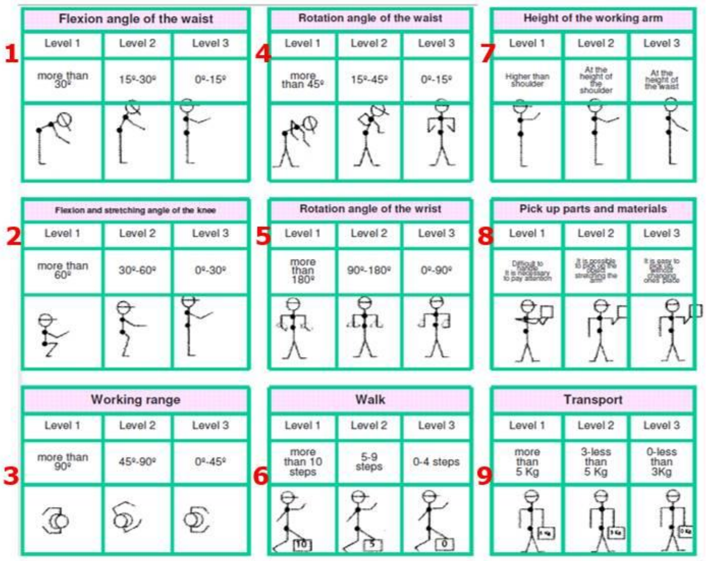
This question was partially answered in Chapter 3, where it has been proposed an intuitive quantitative way (sub-chapter 3.3.2) to investigate the ergonomic strain to which the worker is subjected and by doing so orienting the logic for the task distribution. By analyzing the time spent in angles of discomfort for each body area in each assembly activity, it would be thus possible to earn a further understanding about which activity the robot should take over in order to relieve the worker of the most strenuous tasks. In this sub-chapter, an ergonomic evaluation is carried out on the final designs of the manual and HR collaborative assembly scenarios, with the aim to verify that the proposed task allocation approach allows for an improvement also under an ergonomics point of view.

The methodology to carry out the above-mentioned analysis starts from the tables of activity time percentages spent in discomfort positions (Table) listed by means of the ergonomic tools available in Process Simulate.

To allow for a significative analysis, the actual amount of time (in seconds) of body joint discomfort during each activity has been computed by multiplying each percentage by the respective operation cycle. In order to take into acount the different level of discomfort, the lean concept of MURI [38] was implemented in the ergonomic evaluation methodology.

According to the MURI philosophy, working postures are categorized, for each body region, in the different intervals of joint angle (from 1 to 3), where a discomfort level of 1 is assigned to the least demanding position, whereas the level 3 is assigned to the most demanding ones. Given the similitudes of this lean approach with the one chosen for this study, a quantitative value has been associated to each level of discomfort for the worker (1 for mild, 2 for moderate and 3 for critical).

Figure 21 MURI Body Posture Categories

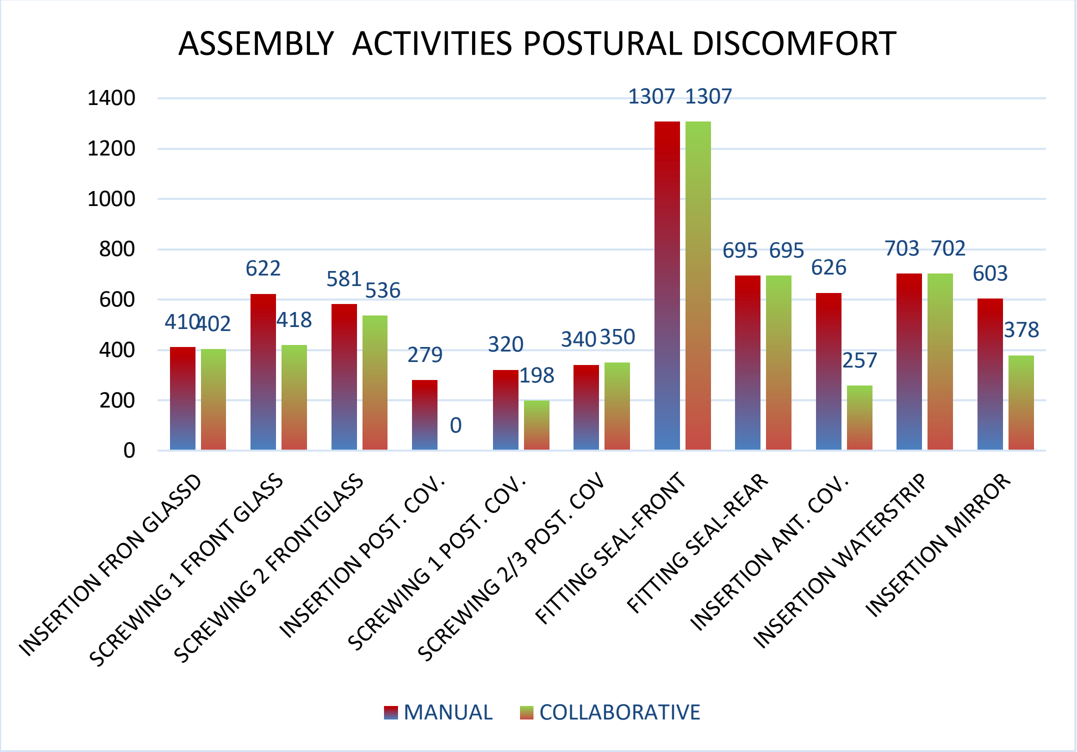


The time intervals that the body joint spend in each posture category have then been multiplied by their respective discomfort level value, the result is thus a set of weighted times for each body area for each activity.

To allow for a more intuitive and easier analysis of the results, following again the principles of MURI, the physical strain to which each body area is subjected to is evaluated by summing all the time intervals (in weighted second) along the whole assembly process. In the same way, in order to assess how physical demanding a certain assembly activity is on the whole upper body, the weighted discomfort time intervals related to each activity have been summed into a single value.

The results of this ergonomic analysis, carried out for the first case study, is reported in the following bar charts (Fig.20-23).

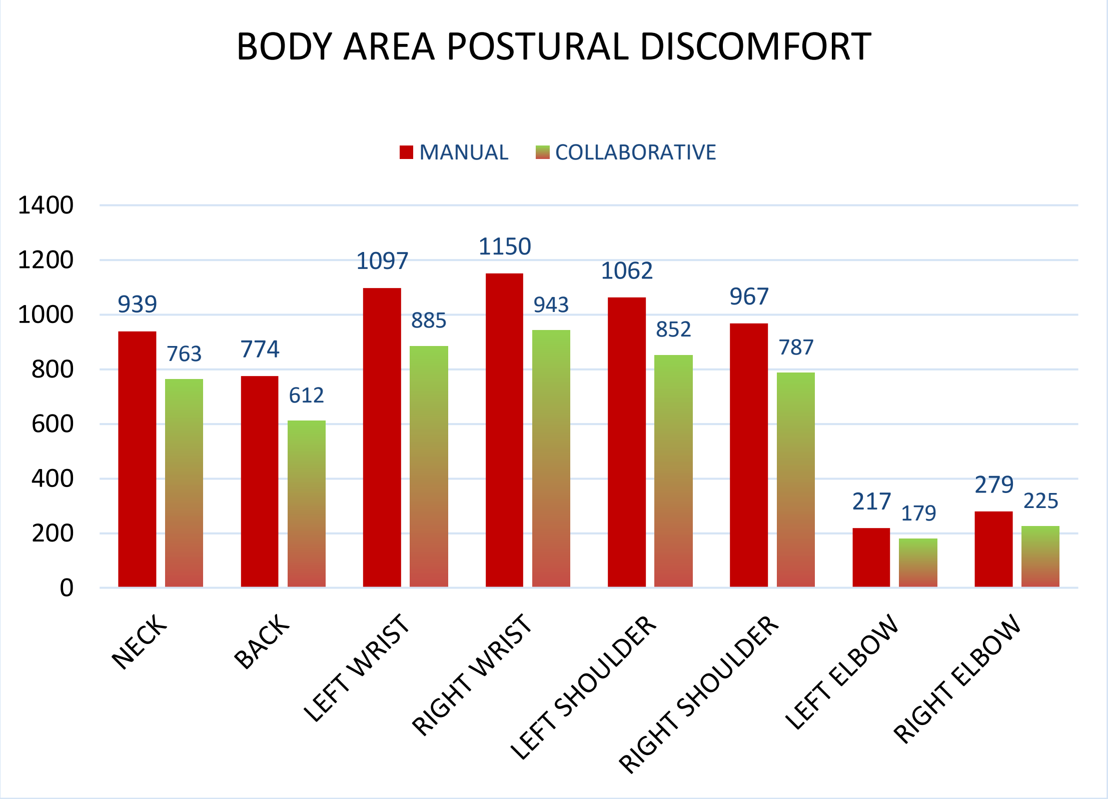
Figure 22 Activities Postural Discomfort Comparison – Case Study #2



Concerning the first assembly scenario, Fig.21 shows that by deploying a collaborative robot a slight ergonomic improvement is achieved for all the activities involved. As expected, the activities showing the most significant improvements are the ones where the robot plays a major role (e.g insertion of the posterior vertical coverage or the positioning of the anterior vertical coverage.).

However the activity showing the highest physical strain (i.e. fitting seal front) does not have ay change; this is due to the fact that fitting a rubber element in a significantly long and thin slots requires an amount of tactfulness and precision that makes the collaborative robot unfit for the role. While implementing a collaborative robot brings several advantages in terms of reachability extension and adaptability, a significant loss of accuracy and precision cabability must be considered.

Figure 23 Body Areas Postural Discomfort Comparison – Case Study #1



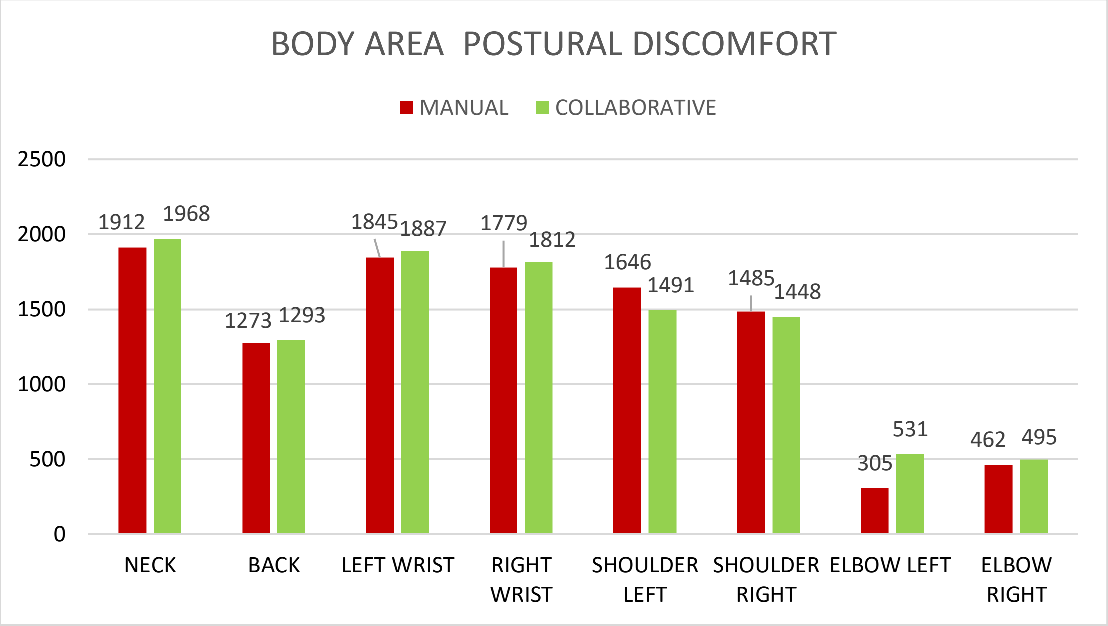
A more significant improvement can be noticed in terms of the stress to which the different body joints are subjected during the whole assembly cycle. If instead of considering the different activities, who might show no differences if the robot is carrying out another task separately, the overall workload is evaluated for each body area, a more significant result is achieved.

It can be noticed how all the upper limbs benefit from the deployment of the robot, and an overall workload decrease is achieved. As mentioned in the preliminary analysis in Chapter 3, the most involved joints are shoulders and wrists.

As expected, by applying the developed task distribution logic those areas are the ones showing the highest improvement in terms of ergonomic strain. This thanks to the fact that alongside the process the robot is taking over several lifting and positioning activities and can aid the worker in the positioning and insertion of few of the components to be assembled.

For the sake of completeness, it is worth mentioning that the elbows are showing extremely low levels of stress due to the fact that differently from the other body joints, for which the software evaluates four different conditions each (e.g. pronation, flection, torsion…etch), the software only considers the elbow when it is in a flection condition, thus leading to a lower value of weighted seconds summed.

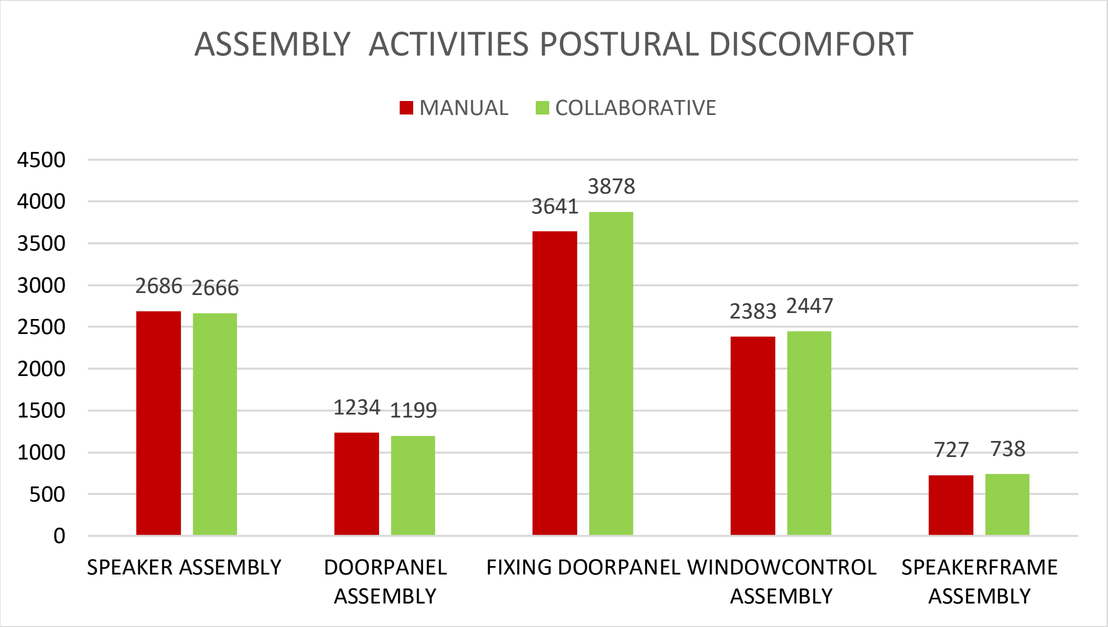
Figure 24 Body Areas Postural Discomfort Comparison – Case Study #2



However, a different ergonomics result is reached if the proposed approach is applied to the second assembly case study. The substantial inefficiency in the deployment of the collaborative robot revealed by the productivity comparative analysis for this scenario can be observed again in the comparison of the manual and collaborative ergonomic assessments.

The analysis of the physical workload of each activity (Fig. 25) and the evaluation of the stress each considered body joint is subjected to (Fig.24) show how no changes in the worker's physical strain are detected. Actually, due to the several handover operation of tools, which require for the worker to steadily hold the tool while the robot grasps it, for some activities the implementation of a cobot results to be detrimental.

Figure 25 Activities Postural Discomfort Comparison – Case Study #2



Hence, as already revealed by the comparison between the manual and collaborative operational cycle times, the deployment of the robotic assistant does not bring any actual benefit neither to the productivity of the cell nor to the safety and postural comfort of the worker.

Finally, by carrying out the safety and ergonomic analysis presented in this chapter, it possible to state that the research questions raised at the very beginning of this study have been answered, the following final chapter will thus discuss the results achieved by the present research, its limitations, and its potential future developments.

CHAPTER SEVEN

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

In this work the nature of the interaction between human and robot to collaboratively carry out assembly task has been studied and presented alongside with the identification and analysis of the factors influencing the suitability and effectiveness for collaborative automation.

The scope of the research was to develop a new structured method that could assess the suitability and effectiveness for automation of assembly tasks in an objective way, ultimately distributing them to worker and robot. In particular, the study was focused on identifying those variables that govern the decision upon whether automate a task or not and derive an objective function that could assign a quantitative automation-score to the examined activities'

First, extensive research of the latest available solutions (theoretical and practical) and a deep analysis of the real industrial case studies available has been carried out with the aim of identifying and gather the decision variables affecting the process. Second, a set of look-up tables, able to describe in a general and objective way the characteristics of assembly activities has been develop, and a multi-criteria decision-making (MCDM) function has been defined with the aim to evaluate manufacturing tasks. Then, a survey questionnaire Likert – based has been developed and distributed; with the aim of defining the scoring values associated to the task describing criteria and the weights in the MCDM function in an objective way.

The statistical analysis applied to the results of the questionnaire lead to a reduction of 12.5% of the items and to an overall increase in the reliability of the questionnaire.

The application of the developed HR task allocation objective function, using the scores derived from the survey, lad to a HR task distribution which improved the assembly process of the first test scenario cycle time of 19,7 % with respect to the manual assembly and of 7,2% with respect to an commonly unstructured approach. Walking activities were reduced by 40,5%, while an overall reduction of worker's physical load has been achieved for all the examined body joints.

The implementation of the proposed HR task classification method to the second test case revealed, on the contrary, a substantial inefficiency in deploying a collaborative robot. The results of the HR task distribution revealed a cycle time efficiency improvement of only 3,3%, which by itself does not justify the implementation of a cobot, while ergonomic conditions have remained substantially unchanged.

Finally, fur a further validation a hazard analysis and risk assessment has been carried out, and it was showed how a virtual simulation can comply with the latest safety standards.

The all-around analysis shows the importance of using a structured human-robot task allocation framework, as the one proposed and developed alongside this study, able to consider an enlarged scope of decision variables evaluated objectively, with consequent apparent benefits in terms of analysis reliability, design cost reduction, productivity efficiency increase and ergonomics improvement.

7.2 Limitations of the study and future work

7.2.1 Limitations

A possible direction of improvement of the proposed approach is to include randomic and statistical elements, as the way tasks have been described so far is purely deterministic. Both the task allocation and the safety validation of the process has been carried out in a deterministic way, this because the available data were of this kind. If data about quality, failure possibility or defective operations were to be available, the proposed approach can be enriched with statistical elements, making its application to real case scenarios more consistent and reliable.

On the practical side, the proposed task allocation method could be better tested and improved if a more developed digital twin were to be available.

In fact, the virtual simulation used in this study to verify the applicability of the new developed approach has been built in what is called ‘event-based mode”: this means that the assembly station is analyzed by itself, without considering the surrounding environment and how it may affect it.

7.2.2 Future Work

Being the research topic of human-robot collaborative automation still in its early stages, the different potential developments of the present study are several.

On a more theoretical side, the task allocation method proposed can be further developed together with the questionnaire related to it, including more decision variables and task describing criteria, with the aim to allow for the proposed approach to be applied to a broader range of scenarios.

In order to further verify the validity of the new task allocation method proposed in this research, it would be interesting to apply it to other manufacturing scenarios that could benefit from collaborative automation and analyze the robustness of the approach and its results, .

On a more practical side, a future development could be to export the available digital twin, still in its early stages of design, to a “line simulation mode’, which means linking it to the whole manufacturing context eventually testing it in a real physical manufacturing environment.

Finally, it would be interesting to apply a reverse approach and study how the station and the process layouts can be modified to make a possible collaborative automation less challenging and more profitable, enlarging the scope of the concepts of “design for automation” from the product itself to the whole assembly process/environment.

APPENDIX A

DATA TABLES

APPENDIX

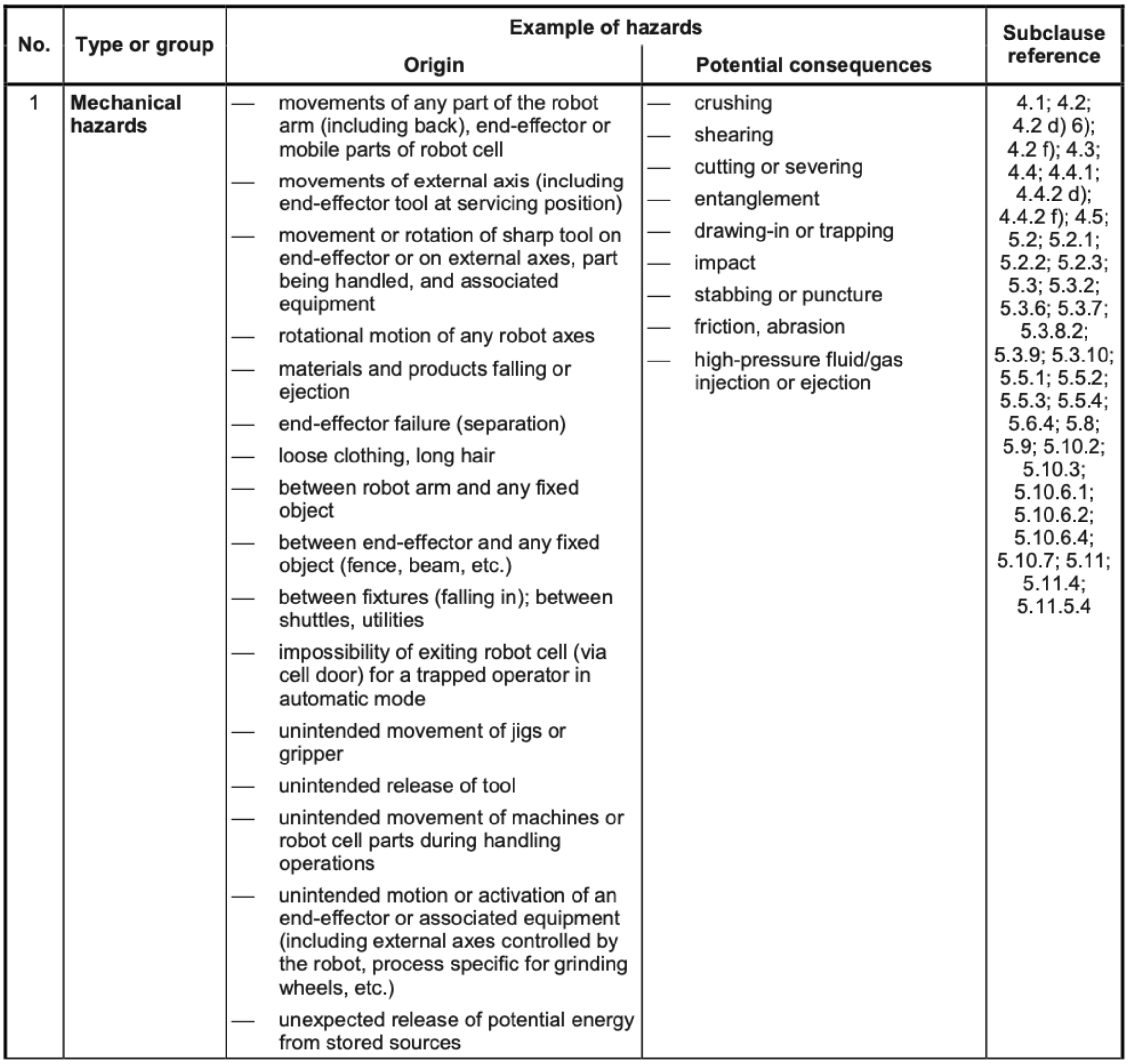
Table A. 1 AMR Technical Specifications

Parameter	Value
Maximum Speed	2 [m/s]
Footprint	31,5 x 22,8 [in]
Maximum Payload	250 [kg]
Accuracy	+- 60 [mm]
Maximum Operation Time	13 [h]
Sensors	3D camera Intel RealSense™ D435 nanoScan3 (front and rear)

Table A. 2 End-Effector Technical Specifications

Specification	Value
Gripper opening [mm]	0 to 155
Gripper weight [kg]	2,3
Object diameter for encompassing [mm]	20 to 155
Maximum recommended payload (encompassing grip) [kg]	10
Maximum recommended payload (fingertip grip) [kg]	2,5
Grip force (fingertip grip) [N]	30 to 70

Table A. 3 List of Significant Hazards



No.	Type or group	Example of hazards		Subclause reference
		Origin	Potential consequences	
1	**Mechanical hazards**	— movements of any part of the robot arm (including back), end-effector or mobile parts of robot cell — movements of external axis (including end-effector tool at servicing position) — movement or rotation of sharp tool on end-effector or on external axes, part being handled, and associated equipment — rotational motion of any robot axes — materials and products falling or ejection — end-effector failure (separation) — loose clothing, long hair — between robot arm and any fixed object — between end-effector and any fixed object (fence, beam, etc.) — between fixtures (falling in); between shuttles, utilities — impossibility of exiting robot cell (via cell door) for a trapped operator in automatic mode — unintended movement of jigs or gripper — unintended release of tool — unintended movement of machines or robot cell parts during handling operations — unintended motion or activation of an end-effector or associated equipment (including external axes controlled by the robot, process specific for grinding wheels, etc.) — unexpected release of potential energy from stored sources	— crushing — shearing — cutting or severing — entanglement — drawing-in or trapping — impact — stabbing or puncture — friction, abrasion — high-pressure fluid/gas injection or ejection	4.1; 4.2; 4.2 d) 6); 4.2 f); 4.3; 4.4; 4.4.1; 4.4.2 d); 4.4.2 f); 4.5; 5.2; 5.2.1; 5.2.2; 5.2.3; 5.3; 5.3.2; 5.3.6; 5.3.7; 5.3.8.2; 5.3.9; 5.3.10; 5.5.1; 5.5.2; 5.5.3; 5.5.4; 5.6.4; 5.8; 5.9; 5.10.2; 5.10.3; 5.10.6.1; 5.10.6.2; 5.10.6.4; 5.10.7; 5.11; 5.11.4; 5.11.5.4

Table A.3. (continued)

No.	Type or group	Example of hazards		Subclause reference
		Origin	Potential consequences	
2	**Electrical hazards**	— contact with live parts or connections (electrical cabinet, terminal boxes, control panels at machine) — confusion of various voltages within a system, electrical cabinet and terminals, i.e. drive power, control power (24 V versus 110 V) — contact with discrete components in the electrical (electronic) circuitry, i.e. capacitors — exposure to arc flash — process using high voltage or high frequency, i.e. electrostatic painting, inductive heating — welding applications using high voltage	— electrocution — shock — burn — projection of molten particles	4.4.1; 5.3.2; 5.3.6; 5.3.7; 5.8.2; 5.10.6.1; 5.10.6.2; 5.10.7
3	**Thermal hazards**	— hot surfaces associated with the end-effector, or associated equipment or work piece (e.g. welding torches, hot materials in forging presses, injection moulding, grinding and de-burring) — cold surfaces or objects (cryogenic processes) — explosive atmosphere caused by the process, i.e. paint (atomized particles, powder painting), flammable solvents, grinding and milling dust — temperature extremes required to support the process [molten materials; ovens for cooking or heating (autoclaves); freezer or chillers, etc.] — flammable materials (inside dust collector systems, cleaning tanks, sealant applicators)	— burn (hot or cold) — radiation injury	5.3; 5.5.2; 5.5.4
4	**Noise hazards**	— specific applications which are sources of high noise (e.g. a water jet cutter, stamping presses, pumps and valving, metal removing operations) — noise level preventing hearing or understanding audible danger warning signals, including inability of persons to coordinate their actions through normal conversation	— loss of hearing — loss of balance — loss of awareness, disorientation — any other (e.g. mechanical) as a consequence of ambient conditions or distraction	Noise is excluded from the scope of this part of ISO 10218
5	**Vibration hazards**	— direct contact with the source — loosening of connections, fasteners — misalignment of components or parts	— fatigue — neurological damage — vascular disorder — impact	4.2 , 4.3, 4.4, 4.5, 5.5.2, 5.5.9
6	**Radiation hazards**	— EMF interference with proper operation of the robot system — exposed to process-related radiation, i.e. arc welding, laser.	— burn — damage to eyes and skin — related illnesses	4.2, 4.3, 4.4, 4.5, 5.5.2, 5.5.9

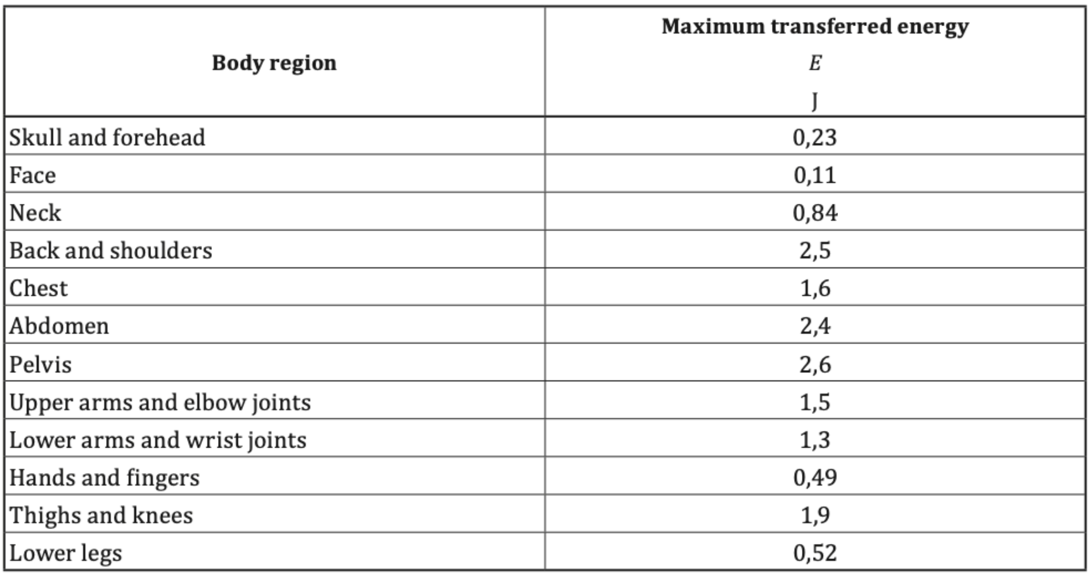
Table A.3. (continued)

No.	Type or group	Example of hazards		Subclause reference
		Origin	Potential consequences	
7	**Material/ substance hazards**	— contact with components covered in harmful fluids — failures of mechanical and electrical components — corrosive fumes and dust	— sensitization — fire — chemical burn — inhalation illnesses	4.2, 4.3, 4.4, 4.5, 5.5.2, 5.5.3
8	**Ergonomic hazards**	— poorly designed teach pendant, HMI touch screen or operator panel (too far or high) — poorly designed loading/unloading post (e.g. long distance between components box location and loading/ unloading area) — poorly designed enabling devices — inappropriate location or identification of controls (e.g. hard to reach) — inappropriate location of components that require access (troubleshooting, repair, adjustment) — obscured hazards, inadequate or blocked local lighting	— unhealthy postures or excessive effort (repetitive strain) — fatigue	4.2 d); 4.3; 4.4; 4.5; 5.3.2; 5.3.13; 5.5; 5.5.2; 5.5.3; 5.9
9	**Hazards associated with environment in which the machine is used**	— installations in earthquake zones — electromagnetic interference or surges in energy source — moisture — temperature	— burn, — disease or illness — slipping, falling — respiratory damage — impact	4.1; 4.2; 5.2; 5.3; 5.5
10	**Combinations of hazards**	— robot system directed to start by one person, but this action is not expected by another person — hazards encountered due to multiple failures/situations — misidentification of actual problem and compound problem by making incorrect or unnecessary actions — action increases severity of harm, i.e. in avoiding a sharp edge, contact is made with a hot surface instead — unintended release of holding devices allowing motion under residual forces (inertia, gravity, spring/energy storage means) — failure of a safeguarding device to function as expected	— any other consequence of combinations of hazards and hazardous situations	4.2; 4.3; 4.4; 4.5; 5.2; 5.3.10; 5.6.3.3; 5.8; 5.9; 5.9.1;

Table A. 4 Biomechanical limits

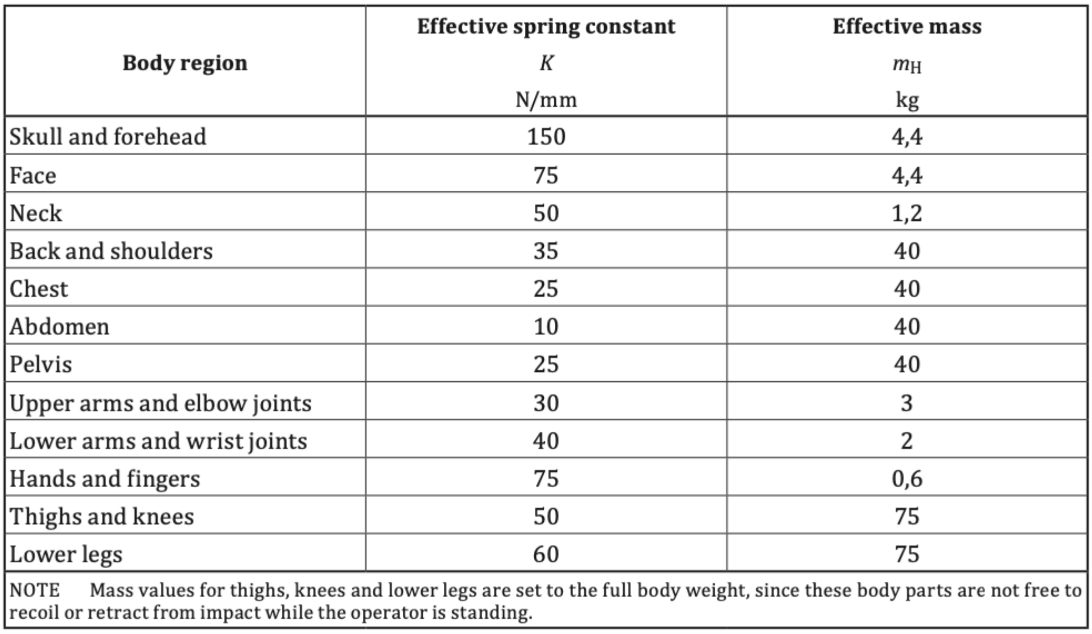
Body region	Specific body area		Quasi-static contact		Transient contact	
			Maximum permissible pressure [a] p_s N/cm^2	Maximum permissible force [b] N	Maximum permissible pressure multiplier [c] P_T	Maximum permissible force multiplier [c] F_T
Skull and forehead [d]	*1*	*Middle of forehead*	*130*	*130*	*not applicable*	*not applicable*
	2	*Temple*	*110*		*not applicable*	
Face [d]	*3*	*Masticatory muscle*	*110*	*65*	*not applicable*	*not applicable*
Neck	4	Neck muscle	140	150	2	2
	5	Seventh neck muscle	210		2	
Back and shoulders	6	Shoulder joint	160	210	2	2
	7	Fifth lumbar vertebra	210		2	2
Chest	8	Sternum	120	140	2	2
	9	Pectoral muscle	170		2	
Abdomen	10	Abdominal muscle	140	110	2	2
Pelvis	11	Pelvic bone	210	180	2	2
Upper arms and elbow joints	12	Deltoid muscle	190	150	2	2
	13	Humerus	220		2	
Lower arms and wrist joints	14	Radial bone	190	160	2	2
	15	Forearm muscle	180		2	
	16	Arm nerve	180		2	
Hands and fingers	17	Forefinger pad D	300	140	2	2
	18	Forefinger pad ND	270		2	
	19	Forefinger end joint D	280		2	
	20	Forefinger end joint ND	220		2	
	21	Thenar eminence	200		2	
	22	Palm D	260		2	
	23	Palm ND	260		2	
	24	Back of the hand D	200		2	
	25	Back of the hand ND	190		2	
Thighs and knees	26	Thigh muscle	250	220	2	2
	27	Kneecap	220		2	
Lower legs	28	Middle of shin	220	130	2	2
	29	Calf muscle	210		2	

Table A. 5 Energy limit values based on the body region model



Body region	Maximum transferred energy E J
Skull and forehead	0,23
Face	0,11
Neck	0,84
Back and shoulders	2,5
Chest	1,6
Abdomen	2,4
Pelvis	2,6
Upper arms and elbow joints	1,5
Lower arms and wrist joints	1,3
Hands and fingers	0,49
Thighs and knees	1,9
Lower legs	0,52

Table A. 6 Efective mass and spring constants for the body model



Body region	Effective spring constant K N/mm	Effective mass m_H kg
Skull and forehead	150	4,4
Face	75	4,4
Neck	50	1,2
Back and shoulders	35	40
Chest	25	40
Abdomen	10	40
Pelvis	25	40
Upper arms and elbow joints	30	3
Lower arms and wrist joints	40	2
Hands and fingers	75	0,6
Thighs and knees	50	75
Lower legs	60	75
NOTE Mass values for thighs, knees and lower legs are set to the full body weight, since these body parts are not free to recoil or retract from impact while the operator is standing.		

APPENDIX B

QUESTIONNAIRE FOR HR TASK ALLOCATION SURVEY

Human-Robot Task Assignment Questionnaire

1. Introduction to the use case

The use case for this research is the **final assembly of the front door** of a car in an automotive manufacturing industry.
The process is currently carried out completely manually by a worker. The cycle time is 5 minutes, and 7 components should be picked from the cart. The cart carries the door and components to the workstation.
The elements are extremely different from one another in terms of shape, size and material (involve glass components, rubber and seal elements, rigid plastic parts and also some screw driving operations are involved).
Aim of this study is to **deploy an autonomous mobile collaborative robot** to help the worker to carry out the assembly tasks in a close degree of collaboration.
Physical interaction between the robot and the worker needs to be enabled, as well as carrying out tasks either jointly or individually but within the same work space.
To allow for this kind of interaction human-robot communication technologies are needed to not only enable safety but also for fast and reliable communication. but

limiting down times and stops of the robot at the minimum to maximize the cell productivity.

2. Objective of the survey

Aim of this research is to develop a **new task assignment method** considering the variables mainly affecting productivity and evaluate them to assess which tasks should be assigned to the robot and which to the worker.
The identified variables are 4: Physical Characteristics of the part to be handled and of the task, HR communication technology required by the task, Safety requirements for the task and Characteristics of the Feeding system.
To allow for an evaluation, each of this variable is divided into specific sub variables to which a set of criteria that can describe the task is assigned.

Aim of this survey is to ask to the participants to assess the importance of a set of criteria describing an assembly task, depending on its importance according to the participant.

Before the start of the questionnaire, please Provide the following Information:

- Education Title:

- Current job position:

3. Questionnaire

- **In the following the scale 1 to 5 is describing the increasing suitability for automation, were 1 is to be intended as "not suitable for automation" whereas 5 is to be intended as "extremely suitable/effective for automation"**

- **In the following question it should not be considered the ergonomics factor, as it will be considered in a separate analysis.**

a. PART CHARACTHERISTC

1) Given the following weight intervals of the components, assign a score according to its suitability to be handled by a cobot, considering its effect on productivity and safety of the worker in a close and fenceless collaboration.

w < 1 kg (2.2 lb)	1	2	3	4	5
1kg (2.2lb) < w < 3 kg (6.6lb)	1	2	3	4	5
3 kg (6.6lb) < w < 5 kg (11lb	1	2	3	4	5
w > 5 kg	1	2	3	4	5

2) Considering the following characteristics assign a score according to their suitability for cobot handling

Part is rigid, force applied by end effector or impacts are not a concern	1	2	3	4	5
Part can be deformed under high force, Shape restores itself after force application	1	2	3	4	5
Part can be deformed under low force Shape needs to be adjusted by worker after robot handling	1	2	3	4	5
Part is shapeless	1	2	3	4	5
No gripping areas available (Special gripper required)	1	2	3	4	5

3) Considering the following degree of fragility of the part to be handled, assign a score according to their suitability for cobot handling, considering an assembly scenario were the activities to be carried out are different one form the other and the parts to be handled are different in terms of shape, size, and material:

Cannot be broken by either crush or impact No fragile surfaces	1	2	3	4	5
Can be indented or broken if crush or Impact at high force occurs	1	2	3	4	5
Can be indented or broken if crush or impact at low force occurs	1	2	3	4	5
Extremely fragile, can be indented or broken just by the end effector force	1	2	3	4	5
A gripping area is available (No special gripper required)	1	2	3	4	5

b. TASK CHARACTHERISTC

4) Considering the following task dexterity requirements, assign a score according to their suitability/effectiveness for automation:

Simple operation, precision not required, rigid motions involved (e.g. pick&place).	1	2	3	4	5
Some flexibility required, positioning requires adjustments.	1	2	3	4	5
Tolerances involved, low haptic, Sensibility required.	1	2	3	4	5
Task requires high levels of dexterity And flexibility (e.g. fitting rubber elements)	1	2	3	4	5

5) According to the following task characteristics, assign a score according to how much they can affect the suitability for automation:

Tactfulness required for the task	1	2	3	4	5
Force must be applied to insert part Into its slot	1	2	3	4	5
No force shall be applied to insert the Part into its slot	1	2	3	4	5
Task doesn’t require tactfulness	1	2	3	4	5

c. Human-robot communication

1) According to the kind of interaction required by the communication device adopted, assign a score according to its suitability for automation and, considering the time required by that specific interaction, its impact on the cycle time and cost:

No action required from worker (e.g. Kinect motion recognition, vision system)s	1	2	3	4	5
No physical interaction required (e.g Verbal commands)	1	2	3	4	5
Physical interaction required, no walking Is necessary (e.g smartwatch)	1	2	3	4	5
Both physical interaction and walking are Necessary (e.g. Fixed screen)	1	2	3	4	5

2) According to the cognitive load that a HR communication device requires to the worker to complete a task, assign score according to its suitability for automation (supposing a trained worker is carrying out the activity):

High Cognitive load (e.g. AR glasses, head mounted speech recognition)	1	2	3	4	5
Moderate cognitive load (e.g. tapping on screen, smartwatch)	1	2	3	4	5
No cognitive load	1	2	3	4	5

(e.g. glove based gesture recognition, distant speech recognition)

3) According to the complexity level of the instructions required for the automation of a certain task, assess its suitability for automation:

Requires demonstration or guidance 1 2 3 4 5
(e.g. teach a movement, show a human how to perform a task)

Requires data messages 1 2 3 4 5
(e.g. point out where the object is or where it should be collected)

Requires simple commands 1 2 3 4 5
(e.g. next action, go, stop)

4) Considering the following degrees of processing time (to be intended compared to other available technologies), asses their suitability/effectiveness for automation, considering their impact on the cycle time

High Processing Time 1 2 3 4 5
(e.g. Hard buttons, joysticks)

Moderate processing time 1 2 3 4 5
(e.g. verbal commands)

Low Processing Time 1 2 3 4 5
(e.g. soft AR buttons, haptic sensors, gesture recognition)

5) Considering the following possible characteristics of the HR communication device used, assess their possible effects on the cycle time and efficiency of the process

The technology is affected by noise 1 2 3 4 5

The technology is not affected by noise 1 2 3 4 5

The technology is not affected 1 2 3 4 5
by visual obstruction

The technology is affected 1 2 3 4 5

by visual obstruction

c. SAFETY REQUIREMENTS

1) According to the handled part/ tool characteristics, assess the level entity of the danger for the worker if the handling task is assigned to the robot

No sharp edges, soft texture, no risk of entanglement	1	2	3	4	5
No sharp edges, chance of entanglement, low friction may occur	1	2	3	4	5
Presence of sharp/ cutting edges	1	2	3	4	5

2) According to the possible identified hazards involved in the task, assess the entity of the danger the worker is exposed to:

Possibility of cutting tools, bruises, quasi static impact	1	2	3	4	5
Possible high energy impact or pinching, difficult to evade the contact	1	2	3	4	5
Possible low energy impact, Transient contact, easy to avoid the contact	1	2	3	4	5
No relevant hazards are detected	1	2	3	4	5

3) According to the relevant distance between the worker and the robot, assign a score based on the possible safety implications:

Worker inside robot work volume, Interaction not expected	1	2	3	4	5
Worker inside robot work zone, Interaction is expected	1	2	3	4	5
Worker inside robot warning volume	1	2	3	4	5
Worker outside robot work/	1	2	3	4	5

warning volume

d. FEEDING CHARACTERISTICS

1) According to the walking distance between the worker and the performed handled/task, how relevant do you think it would be to assign the task to the robot in order to reduce non value added activities (considering an average HR interaction time of 3 seconds):

Walking distance higher than 9 m (30 feet)	1	2	3	4	5
Walking distance between 5m (16 feet) and 9m	1	2	3	4	5
Walking distance between 1m (3 feet) and 5m (16 feet)	1	2	3	4	5
Distance lower than 1 m (3 feet)	1	2	3	4	5

2) Feeding orientation/Mode

According to the following characteristics about part feeding, how would you rate their suitability for robot handling/automation:

No sorting, part of different shape and size are fed through containers or belts without an order	1	2	3	4	5
Parts are sorted but fed in containers Or belts without order	1	2	3	4	5
Parts are kitted, position and orientation cannot be precisely defined	1	2	3	4	5
Parts are kitted and fed at defined position and orientation	1	2	3	4	5

e. VARIABLES RELATIVE IMPORTANCES

As a last step of this survey please rate the relative importance between the four main variables according to your experience.

You can rate their relative importance in terms of their **impact on productivity** on a scale from 1 to 9, where 1 means '**same impact** as" and 9 means 'extremely **impactful** than'.

e.g. if you think that the safety characteristic of the work cell have a much greater impact on productivity than the feeding system characteristics, you can say that safety characteristics have a level of importance of 9 with respect to the characteristics of the feeding system. This means, to be consistent, the feeding characteristics will have a level of importance of 1/9 with respect to safety characteristics.

	Safety characteristics of the workcell	Part/Task Characteristics	HR Communication	Feeding Characteristics
Safety characteristic of the workcell				
Part/Task Characteristics				
HR Communication				
Feeding Characteristics				

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