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Implementation of a Laboratory Case Study for Intuitive Collaboration Between Man and Machine in SME Assembly

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12.1 Introduction

"Industry 4.0" is the name given to the ongoing fourth industrial revolution, which is actually transforming worldwide factories. This concept was initially introduced by a German government strategic initiative in 2011 (Kagermann et al. 2013) and represents the current

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evolution of modern industry. Production systems are shifting from mass production to mass customization logic (Pedersen et al. 2016), by adapting their performance to a globalized, interconnected and volatile market (Chryssolouris 2013). Actually, in order to be competitive and profitable, modern manufacturing companies need further production flexibility and efficiency in terms of lot sizes, variants, and time-to-market. For these reasons, the key point of Industry 4.0 is the integration of adaptable and reconfigurable manufacturing systems and technologies introducing innovative and advanced elements such as cyber-physical systems (CPS), Internet of Things (IoT), and cloud computing for manufacturing purposes (Zhong et al. 2017). In particular, the role of cyber-physical production systems (CPPS) is to connect the physical and the virtual manufacturing world in order to satisfy agile and dynamic production requirements. The goal is the union of conventional production technology and information technology (IT) for the mutual communication of machines and products in an IoT environment (Lu 2017; Penas et al. 2017). Industrial collaborative robots (see Fig. 12.1) are particular kinds of enabling CPSs and one essential technology of Industry 4.0, and allow direct and safe physical human–robot interaction (HRI). Collaborative robotics aims to help operators in production activities through different levels of coexistence, cooperation, and collaboration by supporting humans in less ergonomic, repetitive, and alienating tasks, also considering product and process production efficiency. The main potential advantages are:

- Improvement of operators' work conditions
- Better use of production areas (no physical barriers are required)
- Improvement of workspace accessibility
- Enlargement of production capacity
- Improvement of products and process quality
- Better use of skilled labor.

In particular, according to the definition provided by ISO TS 15066, physical HRI entails hybrid operations in a shared workspace, which is defined as the "*space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently*

Fig. 12.1 A collaborative robot (UR3 model) in a shared workspace (*Source* Smart Mini Factory, unibz [Reproduced with permission from Smart Mini Factory Lab, unibz])

during production operation” (ISO 2016, p. 1). This involves a fenceless production environment where operators and robots can work together in a safe, ergonomic, and efficient way. According to this definition, conventional protective systems for traditional industrial robotics (such as physical barriers for workspace isolation), no longer apply (Matthias and Reisinger 2016). In fact, modern human–robot collaboration (HRC) requires and allows physical interaction between operators and robots. Considering the nature of mechanical risks related to traditional industrial robotics, possible unexpected and unwanted collisions between a non-collaborative robot arm and an operator could be lethal. Fortunately, if safety systems are properly implemented, collaborative robots exceed this adverse and dangerous condition by allowing safe hand-in-hand HRC. Of course, one of the biggest future challenges in the development of collaborative systems is to ensure operators' psycho-physical well-being in terms of occupational health and safety (OHS) while preserving high robot performance. Due to the novelty of the technology, the complexity of the topic and the limited knowledge of companies about the design and management of collaborative systems, small- and medium-sized enterprises (SMEs) should be supported in the proper integration of safe, ergonomic, and efficient HRI. The proposed methodology aims to improve the adoption of collaborative systems into industrial SMEs by providing an efficient methodology for the conversion of manual assembly workstations into collaborative workcells.

12.2 Theoretical Background

Considering that the industrial collaborative robot market is continuously growing (Djuric et al. 2016), it is reasonable to suppose that collaborative assembly will be a crucial application in the near future. A large part of future collaborative systems will arise from existing manual workstations. For this reason, it is necessary to study a structured methodology, which enables production technicians and managers to simply evaluate if it is possible and reasonable to implement a collaborative assembly workstation starting from an existing one, by considering a set of production criteria. The introduction of collaborative robots aims to support operators' work conditions and production performances by improving physical ergonomics, enlarging production capacity and enhancing product and process quality. Since HRC aims to combine human abilities like flexibility, creativity, and decision-making skills with smart machine strengths like accuracy, repeatability, and payload (Siciliano and Khatib 2016), it is advisable to design new collaborative systems by considering the abilities and constraints of both human and robot resources. As a consequence, the layout and the input/output material flows of the new assembly workstation have to be changed according to the abovementioned considerations. Furthermore, due to the fact that both humans and robots will pick, handle, and assemble different components, the logistics aspects have to be reconsidered by evaluating the new hybrid assembly cycle. Of course, the selection of an adequate and process-oriented collaborative gripping technology will be crucial. In addition, suitable robot sensors for object recognition and situation awareness have to be implemented according to specific production and safety requirements. In addition, it will be fundamental to properly manage the organizational effects of the introduction of collaborative systems by balancing internal (inside the workstation) and external (outside the workstation) production parameters (see Fig. 12.2). In fact, the integration of collaborative systems must not create critical points in a well-structured existing workflow and related production environment.

Safety and ergonomics have necessarily to be incorporated into the preliminary design stage of the collaborative assembly workstation. This will be particularly useful to maximize the design effectiveness and to avoid future useless and time-consuming iterations for the adjustments of the related systems once the development of the workstation is partially completed. In other words, it is necessary to provide all the necessary upgrades to the new assembly workstation in order to facilitate an easy and proper integration of the collaborative robot into the existing production environment. To fill the current gap in terms of design knowledge and skills, guidelines and standards for the implementation

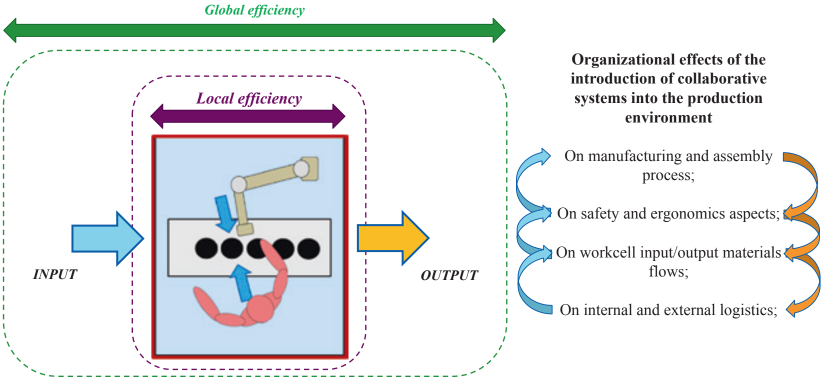

Fig. 12.2 Internal and external effects of the introduction of collaborative robots into existing production systems

of existing and new collaborative systems have to be developed in the near future. This will support an intuitive and barrier-free diffusion of collaborative assembly technologies especially in SMEs.

12.3 Methodology for the Evaluation of Human–Robot Task Allocation

The requirements for the transformation of a manual workstation into a collaborative one should include technical, (physical) ergonomics, qualitative, and finally economic aspects (Gualtieri et al. 2019). The core part of that analysis is to identify which tasks of an existing assembly cycle are more recommended for the robot and which ones for the operator by considering the abovementioned transformation criteria. Preliminary division criteria are provided in Table 12.1. More details about these particular choices and considerations will be discussed in this section.

While designing a transformation process, it is firstly necessary to consider that only certain assembly tasks can be performed efficiently by a robot due to inherent technical limitations (Boothroyd et al. 2010; Boothroyd 2005; Crowson 2006). This is a primary and mandatory constraint which influences all further evaluations. The second constraint will be physical ergonomics. In fact, one of the main purposes of Industry 4.0 is to create anthropocentric factories where the human

Table 12.1 Main guidelines for the preliminary evaluation of human–robot task allocation starting from existing manufacturing activities

Collaborative robot	Operator
Less ergonomic activities which imply physical and/or mental stress for the operator	Activities which imply reasoning ability, interpretation, and responsibility
Activities which imply repetitive tasks and/or which require complex movements for the operators	Activities which imply high handling ability and dexterity
Non value adding (NVA) activities	Value adding (VA) activities
Activities which require standardization and/or quality improvements	Activities which imply flexibility and ability to adapt

factors are the core part of production systems. Finally, it is important to integrate other organizational and economic factors for the development of accurate, flexible, and lean collaborative workstations. The general evaluation workflow and related priorities for the workstation transformation are summarized in Fig. 12.3.

Actually, the main part of the integration of a collaborative into an existing production system will be the division of tasks and activities between the operator and the robot. There are different studies relating to human–robot coordination and the “dynamic” task division in collaborative applications (Chen et al. 2011; Darvish et al. 2018; Liu and Wang 2017), which means a real-time sequencing of activities depending on different operator behaviors and preferences during the assembly cycle. In this situation, the operator can freely choose which task will be the next one indiscriminately. This positive condition of independence could improve cognitive ergonomics conditions, operators’ psychological well-being (Gombolay et al. 2015) and production flexibility (Shen et al. 2015). On the other hand, every task is considered efficaciously executable both by human and robot and as a consequence, there are no technical constraints in terms of robot execution feasibility. For these reasons, it could be useful to firstly identify which tasks of a sequence can be efficiently performed by both humans and robots. This preliminary evaluation allows the designer to successively integrate the dynamic task division approach (variable during the process), by considering the real limits of the robot system. That condition permits a real-time scheduling of the identified unconditioned tasks and as a consequence, allows the operator to freely change the assembly sequence according to his needs and preferences. More details will be explained in Sect. 12.5.1. Since the dynamic task division is an early-stage research topic, this part

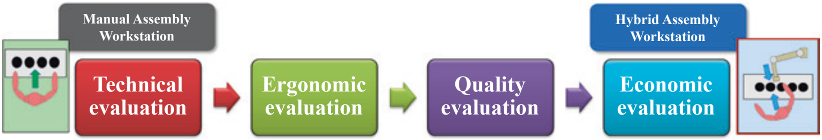

Fig. 12.3 General evaluation workflow and related priorities for the workstation transformation

of the chapter will focus on the preliminary human–robot division of tasks. The proposed discussion will support SME designers to adopt a structured methodology for the preliminary feasibility analysis of the integration of collaborative systems. This involves the evaluation of a manual assembly system in order to decide if a process is suitable or not for collaborative conversion. The main useful data could be: assembly cycle description (including sequences and priorities), task time, task variability, labor and components costs, main geometrical and material features of components, list of value added/not value added activities and physical ergonomics evaluation values. The preliminary task allocation should define if an assembly activity can be performed exclusively by the human (H), exclusively by the robot (R) or equally by the human and robot (H or R) by considering all the proposed considerations. In the following section, a detailed analysis of the evaluation criteria for manual workstation transformation is explained.

12.3.1 Technical Evaluation

The analysis of the technical feasibility of the transformation process aims to investigate if an activity can actually be performed by a robot in an efficient way, by considering its technical limitations of hardware and/or software. In general, it is necessary to verify if a certain type of industrial collaborative robot (equipped with standard commercial devices) is able to perform the feeding, handling and/or assembling of the involved components by using a proper amount of production resources in a suitable time. In this context, the main complexities could arise from product geometry, product dimension, product materials features, assembly location, and assembly sequence organization (Boothroyd et al. 2010; Boothroyd 2005; Crowson 2006). In practice, there are many product or process "technical critical issues" which could complicate or prevent the use of a collaborative robot for assembly or manufacturing activities. Actually, the chance to properly pick and manage a component strictly depends on the type of gripper which it is intended to add to the robot arm (Monkman et al. 2007). A partially completed list of feeding, handling, and assembly critical issues is summarized in Table 12.2.

Table 12.2 Summary of main feeding, handling and assembly critical issues according to the guidelines developed by Boothroyd and Crowson for the design of robotic and automatic assembly (Boothroyd et al. 2010; Boothroyd 2005; Crowson 2006)

Critical issues—Feeding

- The component is magnetic or sticky
- The component is a nest or tangle

Critical issues—Handling

- The component has no symmetry axis
- The component is fragile or delicate
- The component is flexible
- The component is very small or very big (in reference to a human hand)
- The component is light so that air resistance would create conveying problems
- The component is slippery

Critical issues—Assembly

- Components do not have a "datum surface" (reference surface) which simplifies precise positioning during the assembly
- Components cannot be easily orientated
- Components do not include features which allow self-aligning during the assembly
- Components cannot be located before they are released
- Components provide resistance to insertion
- Components do not provide chamfers or tapers that help to guide and position the parts in the correct position
- Components do not have a suitable base part on which to build the assembly
- Components cannot be assembled in layer fashion from directly above (*z*-axis assembly)
- The assembly is overconstrained
- It is difficult to reach the assembly area/the components access for assembly operations is restricted or not easy to reach
- The component and/or the assembly sequence requires high physical dexterity
- The assembly requires high accuracy and/or demanding insertion tolerances
- The assembly needs to reposition the partially completed subassembly, other components or fixtures
- The assembly requires the partial assembly to be reorientated or previously assembled parts to be manipulated
- Components must be compressed during the assembly
- The component and/or the assembly sequence requires two hands for handling
- The component and/or the assembly sequence requires typical human skills (for example touch perception, hearing, ability to interpret situations…)

In general, it is possible to consider two main categories of activities: feeding and handling tasks; assembly tasks. The main reason for the proposed division is that if an operator or a robot needs to assemble one or more components, it is firstly necessary to pick up and handle them. For this motive, a task which requires the assembly also includes the critical issues related to feeding and handling. On the other hand, a task that requires just the feeding or handling does not have to include the assembly critical issues.

A general workflow for the preliminary evaluation of the technical possibility to use a collaborative robot for assembly activities is represented in Fig. 12.4. This guided procedure will help designers to understand if feeding, handling, and/or assembling activities could actually be performed by a certain collaborative robot system (robot arm, gripper, and sensors) efficaciously. In any case, further detailed analysis is necessary for complete comprehension of the problem.

12.3.2 Physical Ergonomic Evaluation

Ergonomics, or human factors, is the science which aims to study the interactions among humans and other elements of a system in order to optimize human well-being and overall system performance (Salvendy 2012). In this context, one of the main goals of the introduction of collaborative robots into manual production systems is to improve an operator's physical conditions by reducing work-related biomechanical stress. A collaborative workstation should be a practical implementation of the so-called "anthropocentric" or "human centered" design, a method which considers the operators' work conditions the main elements of the production system. According to user needs and requirements, the main goals of this design methodology are the improvement of effectiveness, efficiency, well-being, user satisfaction, accessibility, and sustainability by counteracting possible adverse effects of use on human health, safety and performance at the same time (ISO 2010). In this context, the role of the proposed physical ergonomic evaluation stage is to identify if the integration of a collaborative robot could improve operators' physical work

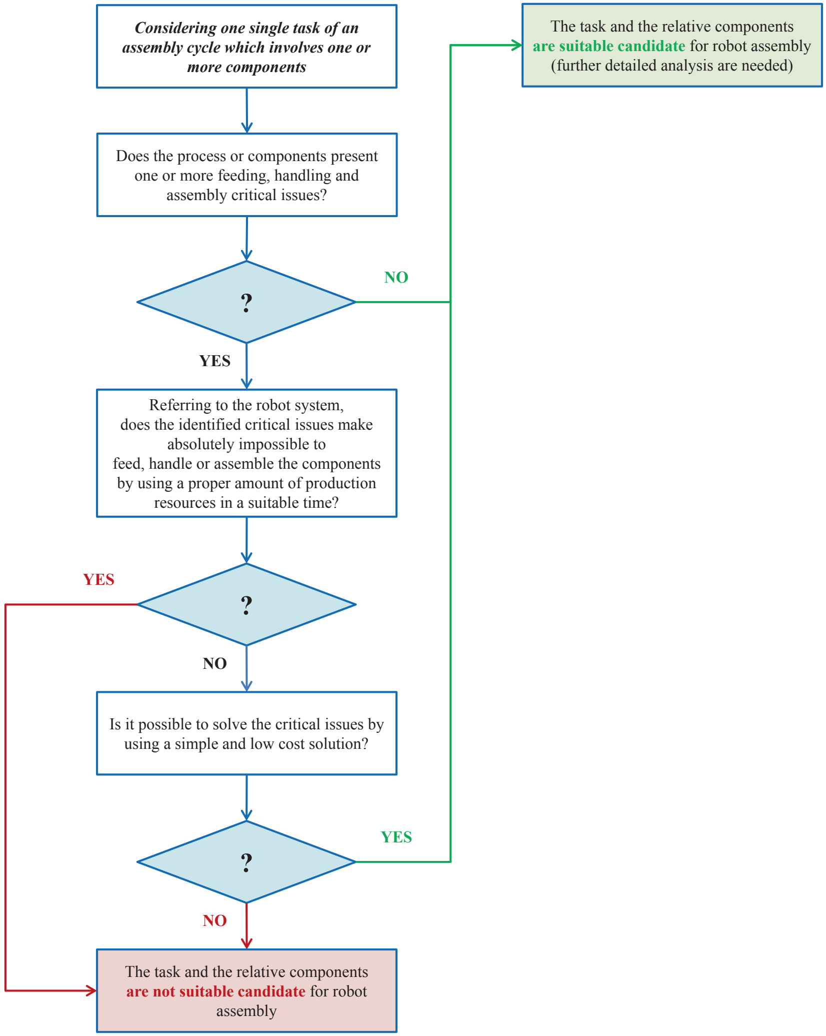

Fig. 12.4 Workflow for the evaluation of the technical possibility to use a collaborative robot for assembly activities

conditions and to quantify the relative benefits. A crucial part of that evaluation is the use of a standard approach for the systematic analysis of the work-related biomechanical stress of the existing workstation. In fact, it is necessary to identify if the future integration of a collaborative robot could really support the operators during manual operations in a physical way. According to the nature of work activities, there are many different recognized methodologies for physical ergonomics evaluation: NIOSH for lifting and carrying (ISO 2003), Snook and Ciriello for whole-body pushing and pulling (ISO 2007a) and Occupational Repetitive Actions (OCRA) for the handling of low loads at high frequency (ISO 2007b). A less detailed, faster and simpler evaluation method is Rapid Upper Limb Assessment (RULA), which can be a useful tool for a preliminary and approximate analysis, particularly focusing on postures. Of course, it is possible to evaluate the physical ergonomics conditions according to other kinds of recognized methodologies or by using the results from different approaches.

12.3.3 Product/Process Quality Evaluation

The product or process quality evaluation aims to investigate if a task or an activity requires improvements in terms of standardization and reduction of process instability or variability. Actually, the concept of quality is often related to the concept of standardization. Standardization improvement means a reduction in related process variability levels. From a manufacturing prospective, variability is defined as an inherent process deviation from a prespecified requirement or nominal value. As a consequence, variability is a negative situation which requires a more controlled condition to achieve the designed process and product quality values (Sanchez-Salas et al. 2017). Obviously, in order to quantify the variability levels, it is necessary to identify one or more process variables to measure. A common possibility could be the task process time of the actual assembly cycle. Once all tasks are mapped and measured, it is useful to identify a list of tasks which present a high level of process variability. Since automation is a useful tool to increase process control, it is advisable to use a collaborative robot for uncontrolled tasks in order to improve the related standardization level.

12.3.4 Economic Evaluation

The economic evaluation aims to recognize the tasks, which can really provide economic value to the final customer according to a cost criteria analysis. Due to the fact that it is necessary to promote easy and fast procedures, a possibility for the implementation of the economic evaluation could be an investigation based on "value added" (VA)/"not value added" (NVA). In industrial management, an NVA task will absorb production resources and/or time by generating unnecessary costs without providing perceived value and satisfaction to the final costumer. In contrast, a VA task will be able to significantly increase the product value and satisfaction to the final customer even if it can generate production costs (Swamidass 2000). In general, in order to reduce and control production costs, it will be advisable to use automation for those activities (and the relative components) which do not provide sufficient economic value to the final customer. In addition, in this case, it will be useful to identify a list of tasks by classifying the related NVA/VA nature through main lean management.

12.3.5 Final Evaluation

Finally, it is necessary to hierarchically relate all the abovementioned concepts in order to achieve a final and all-embracing evaluation of the conversion process. The overall combination of the different evaluation analysis for human–robot task allocation is summarized in Fig. 12.5.

12.4 Application of Intuitive Human–Robot Interaction in the Smart Mini Factory Lab

12.4.1 Introduction to the Smart Mini Factory

The Smart Mini Factory (SMF) is a laboratory of the Free University of Bolzano-Bozen (https://smartminifactory.it/) dedicated to applied research and teaching. Inspired by the concept of a learning factory, it aims to study

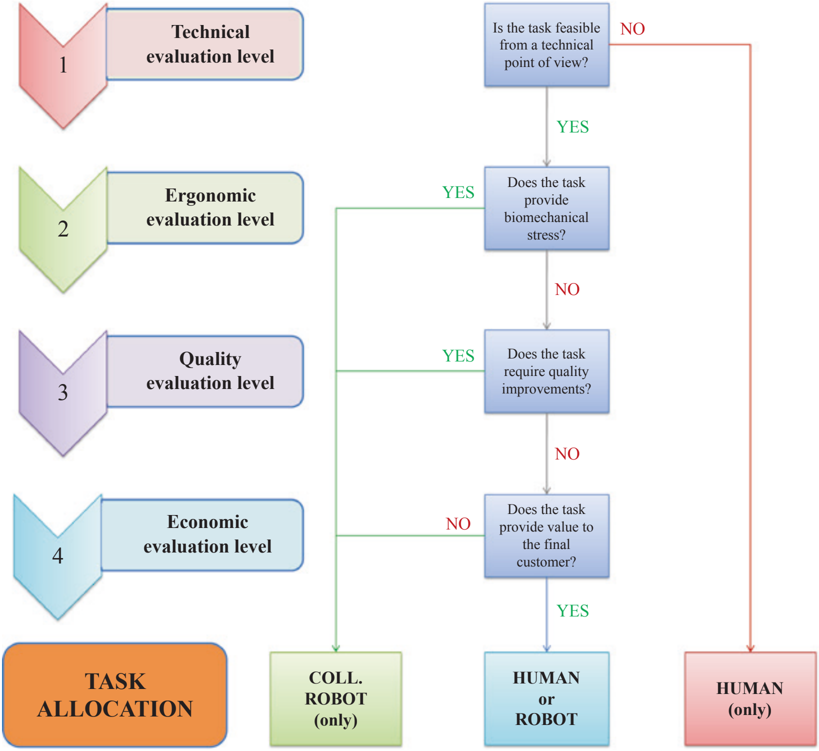

Fig. 12.5 Overall combination of various evaluation analysis for human–robot task allocation

and simulate production systems with a special focus on technologies and methods that enable the fourth industrial revolution. A primary goal is to develop a meeting platform where research, learning, and industry meet to allow common and productive knowledge transfer (Gualtieri et al. 2018). In fact, to achieve knowledge production, diffusion and application through innovation, the laboratory is built to serve three purposes:

- **Research**: company's needs are translated into application-oriented research projects. In addition, research results and know-how are provided for the future.
- **Teaching**: beyond regular lessons and practical sessions, students can develop their study projects as well as final theses and thus gain

valuable experience using state-of-the-art Industry 4.0 systems and automation equipment.
- **Industry**: the SMF is a bridge between industry and research used to supports companies during the implementation of Industry 4.0 concepts by common project collaboration. As a consequence, companies can be involved in the research side as well as in the qualification of their employees via customized industry-oriented seminars for the challenges of Industry 4.0.

Taking these into account, the main requirements of the SMEs in the region and the topics focused on in the SMF lab are the following: Industry 4.0 key enabling technologies, Automation & Robotics, Mechatronics & Electric Drives, Human-Machine Collaboration, Hybrid Assembly Systems, Assistance Systems for Production and Virtual/Augmented Reality. To these, two additional topics that bring the Industry 4.0 concepts and ideas outside the factory are developed or in development: Construction 4.0 and Agro-mechatronics. The topics of human–machine interaction and robotics merge in HRI, which entails physical interaction between operators and collaborative robots. In addition to the Kuka KMR iiwa robotic system, two models of collaborative anthropomorphic robots are available: Universal Robot UR3 and UR10. The main research activities refer to:

- Identification of human-centered robotized solutions for SME
- Development of new methodologies for the evaluation of industrial HRC systems from a safety, economic and technical point of view
- Research on new concepts of collaborative human–robot assembly workstations, taking into account requirements for safety, ergonomics, and production efficiency
- Development of virtual reality solutions for simulation and training for HRI.

12.4.2 Case Study Description

The proposed case study aims to explain the conversion process between an existing manual assembly workstation and a collaborative one.

The manual workstation is located in the assembly simulation line of the SMF laboratory. It is a flexible working area used for training and research in the field of the design of manual and hybrid assembly systems for light industrial products, workplace organization, human-centered design, and ergonomics (see Fig. 12.6). In particular, it is equipped with

Fig. 12.6 Manual assembly workstation for assembly of pneumatic cylinders (Figs. 12.6–12.11 reproduced with permission from Smart Mini Factory Lab, Unibz)

a mobile workbench, a block-and-tackle for lightweight applications, an integrated kanban rack, a working procedures panel, a double lighting system, an industrial automatic screwdriver and a knee lever press where a single operator can completely assemble a pneumatic cylinder (see Fig. 12.7). The main research activities refer to the analysis and optimization of production system performance and operators' work conditions by simulating different assembly circumstances and applications.

Theoretically, it will be advisable to consider the possibility of adopting different types of collaborative robots and grippers in order to identify the more suitable solution according to task sequence and components features. For the proposed simplified case study, a Universal Robot model UR3 (see Fig. 12.9) equipped with a 2-finger Robotiq collaborative gripper (see Fig. 12.8) is used.

The UR3 is the smallest member of the Universal Robots collaborative series. It is a 6-rotating-joint anthropomorphic manipulator suitable

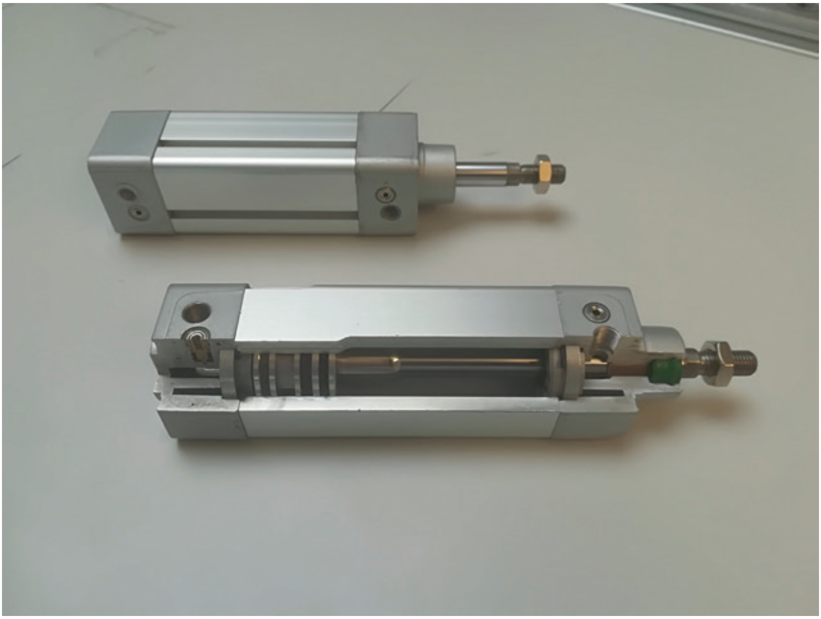

Fig. 12.7 Pneumatic cylinder (As for Figs. 12.6–12.11 the Fig. 12.7 is reproduced with permission from Smart Mini Factory Lab, Unibz)

Fig. 12.8 Robotiq collaborative gripper

for light assembly and high precision tasks. Flexibility and versatility, including an operator-friendly programming device are the main features of this multipurpose robot. Its main technical specifications are (Universal Robot 2019):

- Degrees of freedom: 6 rotating joint
- Payload: 3 kg
- Reach: 500 mm
- Repeatability: ± 0.1 mm
- Power consumption: min 90 W; typical 125 W; max 250 W
- Ambient temperature range: 0–50 °C—at high continuous joint speed, ambient temperature is reduced

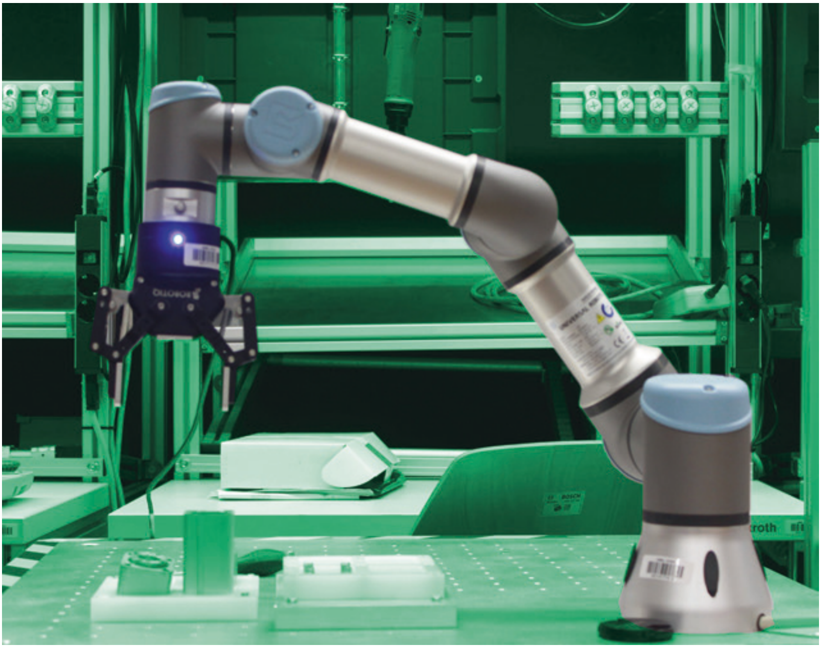

Fig. 12.9 Universal robot UR3 model

- Programming: Polyscope graphical user interface on touchscreen with mounting
- Collaboration operation: 15 advanced adjustable safety functions; TÜV NORD Approved Safety Function; tested in accordance with EN ISO 13849:2008 PL d.

12.4.3 Pneumatic Cylinder Collaborative Assembly

The workpiece which will be analyzed during the proposed case study is a medium-size pneumatic cylinder. The components (see Fig. 12.10) and related subassemblies (see Fig. 12.11) are summarized in Table 12.3.

The current manual assembly cycle is represented in Fig. 12.12.

The actual assembly cycle data are shown in Table 12.4.

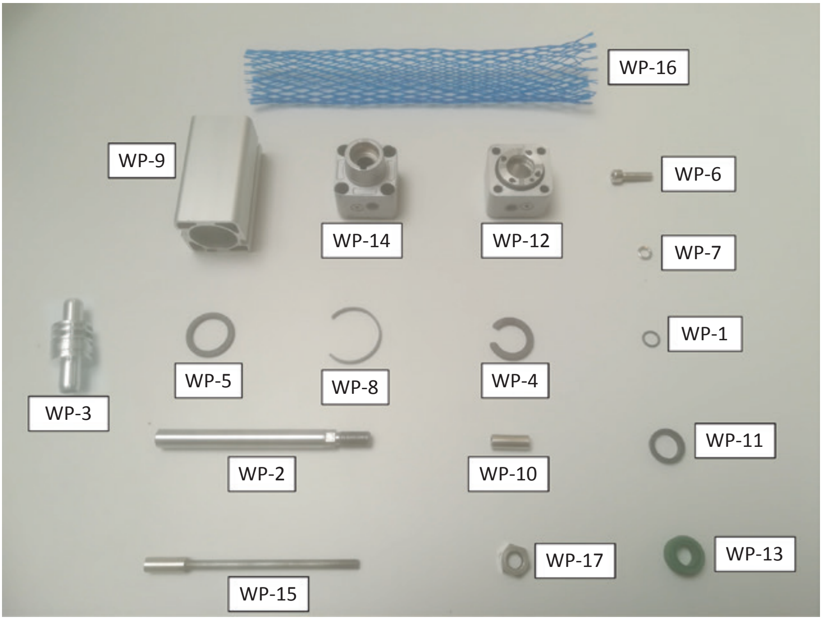

Fig. 12.10 Pneumatic cylinder components

12.4.4 Case Study Evaluation

a) Technical evaluation

According to the pneumatic cylinder description shown previously and by using the guidelines explained in Table 12.2, a preliminary technical evaluation was performed. All the mentioned feeding, handling and assembly critical issues were considered through a detailed visual and operational analysis. It is important to underline that it is of primary importance to really try to perform the tasks in order to understand all the assembly critical points in detail. Table 12.5 shows an example of technical critical issues examination through three feeding and handling tasks.

A further investigation could be performed in order to estimate the importance levels of the identified critical issues. In fact, there might be a difference between the impact of one critical issue with respect to

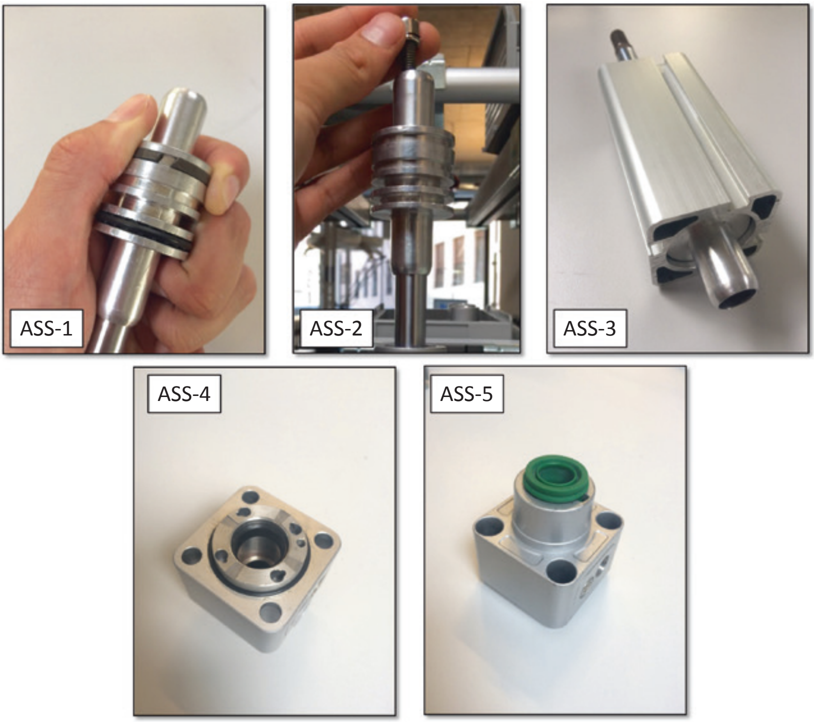

Fig. 12.11 Pneumatic cylinder subassemblies

another in terms of the possibility of using the robot for a certain task. Actually, the use of the same importance level for all the critical issues could be misleading in many cases. The definition of a scale of values could be a good idea for a more detailed technical evaluation. According to the main workflow explained in Fig. 12.5, Table 12.6 investigates the technical feasibility of the analyzed tasks.

As a result, task O5 is not adequate for robotic implementation since it is supposed that the related critical issues make the feeding and the handling of components too complex to be done using a proper amount of production resources in a suitable time. In fact, the ring is magnetic, potentially tangled and also flexible. Those conditions make the automatic gripping impossible since it will be necessary to adopt a

Table 12.3 Components and subassemblies list

	Nr	Code
Part name		
O-ring	1x	WP-1
Piston rod	1x	WP-2
Piston	1x	WP-3
Magnetic ring	1x	WP-4
Piston seal	1x	WP-5
Screw	1x	WP-6
Washer	1x	WP-7
Plastic ring	1x	WP-8
Cylinder	1x	WP-9
Nut 1 (Tie-rod)	4x	WP-10
Seal 1 (black)	2x	WP-11
Base cover	1x	WP-12
Seal 2 (green)	1x	WP-13
Head cover	1x	WP-14
Tie-rod	4x	WP-15
Mesh	1x	WP-16
Nut 2 (piston rod)	1x	WP-17
TOT PIECES		24
Subassembly name		
Piston + Magnetic ring + Piston seal	1x	ASS-1
ASS-1 + Piston rod + O-ring + Screw + Washer	1x	ASS-2
ASS-2 + Plastic ring + Cylinder	1x	ASS-3
Base cover + Seal 1 + Nut 1 (4x)	1x	ASS-4
Head cover + Seal 2 + Seal 1	1x	ASS-5
ASS-3 + ASS-4 + ASS-5 + Tie-rod (4x)	1x	ASS-6
TOT SUBASSEMBLIES		6

very complex solution to properly manage the component (for example a dedicated dispenser for single ring separation, placement, and supply). Task O8 could be a potential candidate. The main problem is that the seal is slightly flexible. In this case, that critical issue does not complicate the related feeding and handling since the utilized gripper can properly manage the component without the necessity of dedicated solutions. Finally, task O27 does not present any critical issues and as a result is a perfect candidate for robotic implementation. From the assembly point of view, Tables 12.7 and 12.8 investigate the technical feasibility of two assembly tasks.

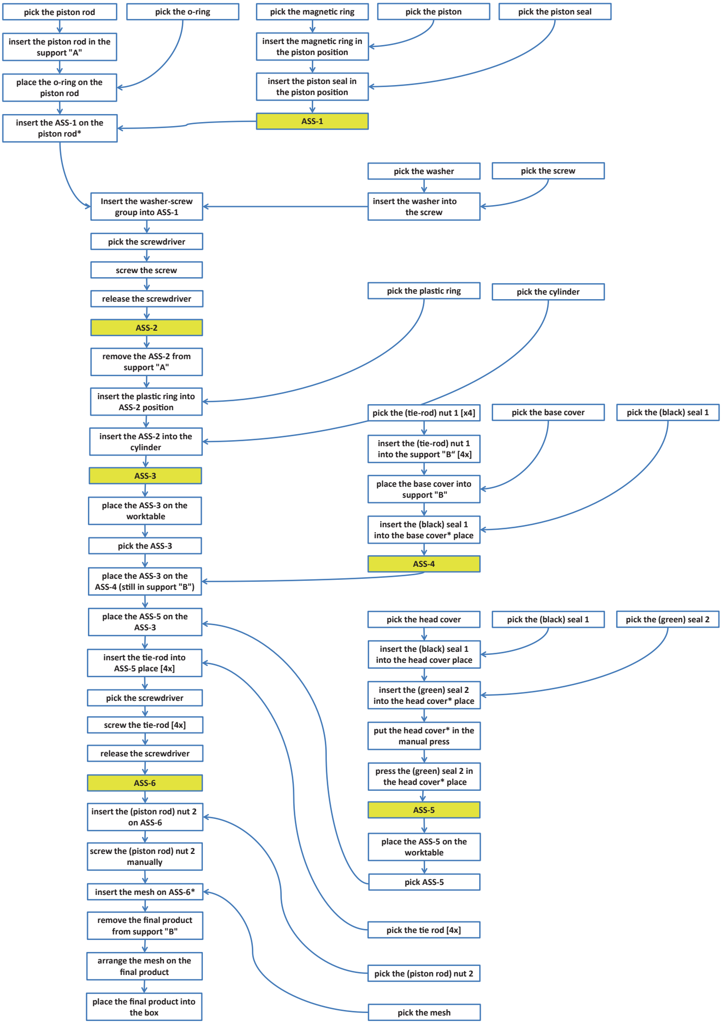

Fig. 12.12 Pneumatic cylinder—manual assembly cycle

O10 could be a potential candidate for robotic implementation if certain adjustments were integrated into the robot system. In fact, since the insertion tolerances are rather demanding, it is advisable to adapt the robotic system for the automatic recognition of the piston—rod

Table 12.4 Manual assembly cycle main data

Nr	Rip	Task	Average task time [s]	Stnd. Dev. [s]
O1	1x	pick the piston rod	2.54	0.35
O2	1x	insert the piston rod in the support "A"	0.80	0.19
O3	1x	pick the o-ring	2.14	1.02
O4	1x	place the o-ring on the piston rod	1.33	0.08
O5	1x	pick the magnetic ring	3.15	1.79
O6	1x	pick the piston	3.67	1.51
O7	1x	insert the magnetic ring in the piston position	4.89	0.87
O8	1x	pick the piston seal	1.61	0,12
O9	1x	insert the piston seal in the piston position	10.13	0.24
O10	1x	insert the ASS-1 on the piston rod*	2.00	0.00
O11	1x	pick the washer	3.31	1.47
O12	1x	pick the screw	1.37	0.64
O13	1x	insert the washer into the screw	1.57	0.26
O14	1x	insert the washer-screw group into ASS-1	1.27	0.18
O15	1x	pick the screwdriver	(/)	(/)
O16	1x	set the screwdriver head (if it is necessary)	(/)	(/)
O17	1x	screw the screw	3.28	1.12
O18	1x	release the screwdriver	(/)	(/)
O19	1x	remove the ASS-2 from support "A"	1.30	0.44
O20	1x	pick the plastic ring	2.59	0.30
O21	1x	insert the plastic ring into ASS-2 position	3.00	0.44
O22	1x	pick the cylinder	5.45	2.18
O23	1x	insert the ASS-2 into the cylinder	5.13	0.60
O24	1x	place the ASS-3 on the worktable	17.42	12.90
O25	4x	pick the (tie-rod) nut 1	8.21	0.61
O26	4x	insert the (tie-rod) nut 1 into the support "B"	9.18	12.1
O27	1x	pick the base cover	1.85	0.56
O28	1x	place the base cover into support "B"	1.62	0.79
O29	1x	pick the (black) seal 1	5.61	0.42
O30	1x	insert the (black) seal 1 into the base cover* place	6.15	2.13
O31	1x	pick the head cover	0.51	0.06
O32	1x	pick the (black) seal 1	4.44	0.86
O33	1x	insert the (black) seal 1 into the head cover place	4.03	1.11

(continued)

Table 12.4 (continued)

Nr	Rip	Task	Average task time [s]	Stnd. Dev. [s]
O34	1x	pick the (green) seal 2	3.33	2.06
O35	1x	insert the (green) seal 2 into the head cover* place	4.35	1.67
O36	1x	put the head cover* in the manual press	2.17	0.84
O37	1x	press the (green) seal 2 in the head cover* place	2.52	0.91
O38	1x	place the ASS-5 on the worktable	3.29	0.93
O39	1x	pick the ASS-3	1.56	0.27
O40	1x	place the ASS-3 on the ASS-4 (still in support "B")	2.86	1.48
O41	1x	pick the ASS-5	2.01	0.58
O42	1x	place the ASS-5 on the ASS-3	3.10	1.35
O43	4x	pick the tie-rod	5.99	1.23
O44	4x	insert the tie-rod into ASS-5 place	5.06	2.15
O45	1x	pick the screw driver	(/)	(/)
O46	1x	set the screwdriver head (if it is necessary)	(/)	(/)
O47	4x	screw the tie-rod	7.34	4.27
O48	1x	release the screwdriver	(/)	(/)
O49	1x	pick the (piston rod) nut 2	2.85	1.08
O50	1x	insert the (piston rod) nut 2 on ASS-6	2.47	1.53
O51	1x	screw the (piston rod) nut 2 manually	3.61	1.50
O52	1x	pick the mesh	1.96	0.39
O53	1x	insert the mesh on ASS-6*	1.95	1.04
O54	1x	remove the final product from support "B"	2.26	0.99
O55	1x	arrange the mesh on the final product	1.97	0.78
O56	1x	place the final product into the box	1.96	0.57

* means that the involved parts or subassemblies are partially assembled with other components

coupling in order to avoid insertion errors. There are two main possible solutions. The first one is the adoption of a vision system which allows the visual recognition of the components and the related insertion direction. That system could also be useful for other feeding and assembly applications. Unfortunately, the cost would be quite high and a detailed analysis is required in order to estimate the related return on investments. Another possibility could be the use of the robot power

Table 12.5 Examples of technical evaluation of feeding and handling tasks

Critical issue typology		Feeding critical issues		Handling critical issues					
Nr	**Task**	The component is magnetic or sticky	The component is a nest or tangle	The component has no symmetry axis	The component is fragile/delicate	The component is flexible	The component is very small or very big (referring to a human hand)	The component is light so that air resistance would create conveying problems	The component is slippery
O5	Pick the magnetic ring	YES	YES	NO	NO	YES	NO	NO	NO
O8	Pick the piston seal	NO	NO	NO	NO	YES	NO	NO	NO
O27	Pick the base cover	NO	NO	NO	NO	NO	NO	NO	NO

Table 12.6 Technical evaluation of tasks O5, O8, and O27 according to main critical issues analysis and technical evaluation workflow

Criteria	O5 Pick the magnetic ring	O8 Pick the piston seal	O27 Pick the base cover
Do the process or components present one or more feeding, handling and assembly critical issues?	YES	YES	NO
Referring to the robot system, does the identified critical issues make it absolutely impossible to feed, handle or assemble the components by using a proper amount of production resources in a suitable time?	YES	NO	(/)
Is it possible to solve the critical issues by using a simple and low-cost solution?	(/)	Not necessary	(/)
FINAL EVALUATION	**Human only (not suitable for robot)**	**Suitable for robot with no modifications**	**Suitable for robot with no modifications**

and force control system (which is an inherent peculiarity of collaborative robots) to delicately and systematically touch the rod with the gripped piston in order to find the suitable insertion direction. This solution does not require additional systems and as a consequence it will be totally free. On the other hand, it requires medium-high programming skills.

O9 is totally unsuitable for robotic implementation with the selected gripper. In fact, there are different critical issues which strongly limit an automatic assembly. For example, conditions like the need for high physical dexterity, the request for two hands for handling the components and the need to compress parts during the assembly operations

Table 12.7 Examples of technical evaluation of assembly tasks

Critical issues	Task	
	O9 Insert the piston seal in the piston position	O10 Insert the ASS-1 on the piston rod*
The component is magnetic or sticky	NO	NO
The component is a nest or tangle	NO	NO
The component has no symmetry axis	NO	NO
The component is fragile or delicate	NO	NO
The component is flexible	YES	NO
The component is very small or very big (in reference to a human hand)	NO	NO
The component is light so that air resistance would create conveying problems	NO	NO
The component is slippery	NO	NO
Components do not have a "datum surface" (reference surface) which simplifies precise positioning during the assembly	NO	NO
Components cannot be easily orientated	NO	NO
Components do not include features which allow self-aligning during the assembly	NO	NO
Components cannot be located before they are released	YES	NO
Components provide resistance to insertion	YES	NO
Components do not provide chamfers or tapers that help to guide and position the parts in the correct position	NO	NO
Components do not have a suitable base part on which to build the assembly	NO	NO
Components cannot be assembled in layer fashion from directly above (z-axis assembly)	YES	NO
The assembly is overconstrained	NO	NO
It is difficult to reach the assembly area / the components access for assembly operations is restricted or not easy to reach	NO	NO
The assembly requires high accuracy and/or demanding insertion tolerances	NO	YES
The component and/or the assembly sequence requires high physical dexterity	YES	NO
The assembly needs to reposition the partially completed sub-assembly, other components or fixtures	YES	YES
The assembly needs to reorient the partial assembly or to manipulate previously assembled parts	YES	YES
Components need to be compressed during the assembly	YES	NO
The component and/or the assembly sequence requires two hands for handling	YES	NO
The component and/or the assembly sequence require typical human skills (for example touch perception, hearing, ability to interpret situations…)	YES	NO

Table 12.8 Technical evaluation of task O9 and O10 according to main critical issues analysis and technical evaluation workflow

Criteria	O9 Insert the piston seal in the piston position	O10 Insert the ASS-1 on the piston rod*
Does the process or components present one or more feeding, handling and assembly critical issues?	YES	YES
Referring to the robot system, does the identified critical issues make it absolutely impossible to feed, handle or assemble the components by using a proper amount of production resources in a suitable time?	YES	NO
Is it possible to solve the critical issues by using a simple and low-cost solution?	YES	YES
FINAL EVALUATION	**Human only (not suitable for robot)**	**Suitable for robot with modifications**

* means that the involved parts or subassemblies are partially assembled with other components

make the components absolutely impossible to feed, handle, or assemble by using a proper amount of production resources in a suitable time. For these reasons, the analyzed task is reasonably performable only by an operator. The list of results for all the task technical evaluation is provided in Table 12.12 at the end of this section.

b) **Physical ergonomics evaluation**

For a preliminary analysis, the RULA method is selected. Considering the static muscle activity and the force caused on the upper limbs, this method is appropriate for the analysis of upper body activities and it involves body part diagrams integrated with the code for joint angles, body postures, load/force, coupling, and muscle activity. It investigates the exposure of individual workers to risk factors associated with work-related musculoskeletal disorders (Karwowski and Marras 2003). The outputs are risk level scores on a given scale to indicate the risk effects, as shown in Table 12.9.

In general, according to the results of the technical evaluation, if the RULA analysis of the selected tasks shows a value equal to or higher than three, it is necessary to deeply understand the problem's root-cause in order to provide a practical solution. In this case, the use of a collaborative robot should be a good option for improving related physical

Table 12.9 RULA action levels and relative task allocation

RULA value	Action level
1;2	**Action level 1:** the posture is acceptable if it is not maintained or repeated for long periods
3;4	**Action level 2:** further investigations are needed and changes may be required
5;6	**Action level 3:** investigations and changes are required soon
7 +	**Action level 4:** investigations and changes are required immediately

Table 12.10 List of tasks which present a RULA index value equal to or higher than three and which could potentially be performed by the robot from a technical point of view

Nr	Rip	Task	RULA INDEX
O1	1x	pick the piston rod	3
O3	1x	pick the o-ring	3
O6	1x	**pick the piston**	**4**
O8	1x	pick the piston seal	3
O10	1x	insert the ASS-1 on the piston rod*	3
O11	1x	pick the washer	3
O12	1x	pick the screw	3
O17	1x	screw the screw	3
O19	1x	remove the ASS-2 from support "A"	3
O20	1x	pick the plastic ring	3
O22	1x	pick the cylinder	3
O25	**4x**	**pick the (tie-rod) nut 1**	3
O27	1x	pick the base cover	3
O29	1x	pick the (black) seal 1	3
O31	1x	pick the head cover	3
O32	1x	pick the (black) seal 1	3
O34	1x	pick the (green) seal 2	3
O36	1x	put the head cover* in the manual press	3
O42	1x	place the ASS-5 on the ASS-3	3
O43	**4x**	**pick the tie-rod**	3
O44	**4x**	**insert the tie-rod into ASS-5 place**	3
O47	**4x**	**screw the tie-rod**	**4**
O49	1x	pick the (piston rod) nut 2	3
O52	1x	**pick the mesh**	**4**
O56	1x	place the final product into the box	3

ergonomics. The list of results for all the task physical ergonomics evaluation is provided in Table 12.12 at the end of this section. Starting from the tasks which could potentially be performed by the robot from a technical point of view, it is necessary to identify the ones with the highest priority from a physical ergonomic point of view. A first classification is provided in Table 12.10.

The tasks which are highlighted in red are the ones with the highest impact from a physical ergonomics point of view. In fact, the related

RULA index value is equal to four (O6 and O52) or equal to three but presenting a non-negligible number of repetitions per task (O25, O43, O44, and O47), a condition which can lead to long-term physical strain. Of course, a large part of the identified tasks could be solved using different kinds of organizational solutions (i.e., by changing the manual station layout—a probable valid solution for all the identified feeding tasks). On the other hand, in particular cases, the use of a robot could be very interesting. Task O47 presents a typical example of physical stress provided by screw operations. The number of repetitions combined with a medium RULA index makes that task an excellent candidate for automation. In addition, tasks O44 and O45 can be easily joined with task O47 in order to create an overall activity (pick, insert, and screw the tie-rods) which would be perfect for the use of the collaborative robot.

c) **Quality evaluation**

It is possible to preliminarily analyze process variability through the coefficient of variation (CV). *CV* is a parameter which can be used to measure and qualify production systems' variability starting from a set of data which are quite easy to obtain and commonly utilized in manufacturing process analysis and optimization. *CV* is defined as the ratio between the standard deviation (σ) and the mean value (*Xm*) (Nwanya et al. 2016):

$$CV = \frac{\sigma}{Xm}$$

According to the definition of *CV*, it is possible to have three different process variability categories: low process variability ($CV = 0 \div 0.75$), moderate process variability ($CV = 0.75 \div 1.33$) and high process variability ($CV > 1.33$). The list of results for all the task quality evaluation is provided in Table 12.12 at the end of this section. Starting from the tasks which could potentially be performed by the robot from a technical point of view, it is necessary to identify the tasks with high process variability. According to the collected data, there is only one high-variability process in the analyzed case study (O26). In fact, a large number of the activities present a value of *CV* lower than 0.50 (see Fig. 12.13), which means that the actual assembly is qualitatively under control according to this parameter. Further investigation could be undertaken by combining the *CV* values with the strategic importance of operations and/or tasks (i.e., by considering the components' economic value). Nevertheless, after a preliminary quality evaluation, O26 would be perfect for the use of the collaborative robot.

d) **Economic evaluation**

For a preliminary analysis, it is possible to categorize the cycle tasks as follows: grasping, handling, moving, positioning as NVA tasks; insertion, fastening, fixing, assembly as VA tasks. It is possible to recognize the tasks' typology just by a visual inspection. According to that classification and starting from the tasks, which could potentially be performed by the robot from a technical point of view, Table 12.11 summarizes the proposed economic division.

According to this classification, all the tasks which are classified as NVA are good candidates for the use of the collaborative robot. In fact, these activities will absorb production resources and/or time by generating unnecessary costs without providing perceived value and satisfaction to the final customer. That condition justifies the use of automation for the execution of these tasks.

e) **Final evaluation**

Finally, it is necessary to combine all the single evaluation results by using the hierarchical approach proposed in Fig. 12.5. This process allows the designer to have a preliminary and approximate estimation of the human–robot task division. After the validation of the task allocation, it will be possible to start the design of the collaborative workstation layout by using a set of structured data. Table 12.12 explains the overall evaluation results.

Actually, the final task allocation will be defined by the hierarchical contribution of every single evaluation. According to the proposed

Table 12.11 VA/NVA classification of tasks which could potentially be performed by the robot from a technical point of view

Nr	Task	Activity type	Classification
O1	pick the piston rod	grasping, handling, moving, positioning	NVA
O2	insert the piston rod in the support "A"	insertion, fastening, fixing, assembly	VA
O3	pick the o-ring	grasping, handling, moving, positioning	NVA
O6	pick the piston	grasping, handling, moving, positioning	NVA
O8	pick the piston seal	grasping, handling, moving, positioning	NVA
O10	insert the ASS-1 on the piston rod*	insertion, fastening, fixing, assembly	VA
O11	pick the washer	grasping, handling, moving, positioning	NVA
O12	pick the screw	grasping, handling, moving, positioning	NVA
O14	insert the washer-screw group into ASS-1	insertion, fastening, fixing, assembly	VA
O17	screw the screw	insertion, fastening, fixing, assembly	VA
O19	remove the ASS-2 from support "A"	grasping, handling, moving, positioning	NVA
O20	pick the plastic ring	grasping, handling, moving, positioning	NVA
O22	pick the cylinder	grasping, handling, moving, positioning	NVA
O24	place the ASS-3 on the worktable	grasping, handling, moving, positioning	NVA
O25	pick the (tie-rod) nut 1	grasping, handling, moving, positioning	NVA
O26	insert the (tie-rod) nut 1 into the support "B"	insertion, fastening, fixing, assembly	VA
O27	pick the base cover	grasping, handling, moving, positioning	NVA
O28	place the base cover into support "B"	insertion, fastening, fixing, assembly	VA
O29	pick the (black) seal 1	grasping, handling, moving, positioning	NVA
O31	pick the head cover	grasping, handling, moving, positioning	NVA
O32	pick the (black) seal 1	grasping, handling, moving, positioning	NVA
O34	pick the (green) seal 2	grasping, handling, moving, positioning	NVA
O36	put the head cover* in the manual press	grasping, handling, moving, positioning	NVA
O38	place the ASS-5 on the worktable	grasping, handling, moving, positioning	NVA
O39	pick the ASS-3	grasping, handling, moving, positioning	NVA
O40	place the ASS-3 on the ASS-4 (still in support "B")	insertion, fastening, fixing, assembly	VA
O41	pick the ASS-5	grasping, handling, moving, positioning	NVA
O42	place the ASS-5 on the ASS-3	insertion, fastening, fixing, assembly	VA
O43	pick the tie-rod	grasping, handling, moving, positioning	NVA
O44	insert the tie-rod into ASS-5 place	insertion, fastening, fixing, assembly	VA
O47	screw the tie-rod	insertion, fastening, fixing, assembly	VA
O49	pick the (piston rod) nut 2	grasping, handling, moving, positioning	NVA
O52	pick the mesh	grasping, handling, moving, positioning	NVA
O54	remove the final product from support "B"	grasping, handling, moving, positioning	NVA
O56	place the final product into the box	grasping, handling, moving, positioning	NVA

framework (see Fig. 12.5), the task allocation logic can be summarized in Table 12.13.

A further design stage would be to unify, in terms of use of resources (human or robot), different tasks which are related to the same activity. For example, task O1 (R) and O2 (H or R) are successive and related to the same component. In this case, it is reasonably advisable to perform these tasks by using the collaborative robot for both the operations. On the other hand, even if tasks O3 (H) and task O4 (R) are in the same condition as previous tasks, it is not useful to perform them separately for an efficiency reason. In fact, the exchange of the component

Table 12.12 Overall and final evaluation results

Nr	Task	Technical evaluation	Ergonomics evaluation		Quality evaluation		Economics evaluation		FINAL RESULTS (task allocation)
		Technical task allocation	RULA index value	Ergonomics task allocation	CV value	Quality task allocation	VA/NVA classification	Economic task allocation	
O1	pick the piston rod	H or R	3	H or R	0.14	H or R	N.V.A.	R	R
O2	insert the piston rod in the support "A"	H or R	2	H or R	0.24	H or R	V.A.	H or R	H or R
O3	pick the o-ring	H or R	3	H or R	0.48	H or R	N.V.A.	R	R
O4	place the o-ring on the piston rod	H	2	H or R	0.06	H or R	V.A.	H or R	H
O5	pick the magnetic ring	H	3	H or R	0.57	H or R	N.V.A.	R	H
O6	pick the piston	H or R	4	R	0.41	H or R	N.V.A.	R	R
O7	insert the magnetic ring in the piston position	H	2	H or R	0.18	H or R	V.A.	H or R	H
O8	pick the piston seal	H or R	3	H or R	0.07	H or R	N.V.A.	R	R
O9	insert the piston seal in the piston position	H	3	H or R	0.02	H or R	V.A.	H or R	H
O10	insert the ASS-1 on the piston rod*	H or R	3	H or R	0.00	H or R	V.A.	H or R	H or R
O11	pick the washer	H or R	3	H or R	0.44	H or R	N.V.A.	R	R
O12	pick the screw	H or R	3	H or R	0.47	H or R	N.V.A.	R	R
O13	insert the washer into the screw	H	2	H or R	0.16	H or R	V.A.	H or R	H
O14	insert the washer-screw group into ASS-1	H or R	2	H or R	0.14	H or R	V.A.	H or R	H or R
O15	pick the screwdriver	(/)	(/)	(/)	(/)	(/)	(/)	(/)	(/)
O16	set the screwdriver head (if it is necessary)	(/)	(/)	(/)	(/)	(/)	(/)	(/)	(/)
O17	screw the screw	H or R	3	H or R	0.34	H or R	V.A.	H or R	H or R
O18	release the screwdriver	(/)	(/)	(/)	(/)	(/)	(/)	(/)	(/)
O19	remove the ASS-2 from support "A"	H or R	3	H or R	0.34	H or R	N.V.A.	R	R
O20	pick the plastic ring	H or R	3	H or R	0.11	H or R	N.V.A.	R	R
O21	insert the plastic ring into ASS-2 position	H	2	H or R	0.15	H or R	V.A.	H or R	H
O22	pick the cylinder	H or R	3	H or R	0.40	H or R	N.V.A.	R	R
O23	insert the ASS-2 into the cylinder	H	2	H or R	0.12	H or R	V.A.	H or R	H

(continued)

Table 12.12 (continued)

O24	place the ASS-3 on the worktable	H or R	2	H or R	0.74	H or R	N.V.A.	R	R
O25(4x)	pick the (tie-rod) nut 1	H or R	**3**	H or R	0.07	H or R	N.V.A.	R	R
O26(4x)	insert the (tie-rod) nut 1 into the support "B"	H or R	2	H or R	**1.31**	R	V.A.	H or R	R
O27	pick the base cover	H or R	3	H or R	0.30	H or R	N.V.A.	R	R
O28	place the base cover into support "B"	H or R	2	H or R	0.49	H or R	V.A.	H or R	H or R
O29	pick the (black) seal 1	H or R	3	H or R	0.08	H or R	N.V.A.	R	R
O30	insert the (black) seal 1 into the base cover* place	H	2	H or R	0.35	H or R	V.A.	H or R	H
O31	pick the head cover	H or R	3	H or R	0.11	H or R	N.V.A.	R	R
O32	pick the (black) seal 1	H or R	3	H or R	0.19	H or R	N.V.A.	R	R
O33	insert the (black) seal 1 into the head cover place	H	2	H or R	0.28	H or R	V.A.	H or R	H
O34	pick the (green) seal 2	H or R	3	H or R	0.62	H or R	N.V.A.	R	R
O35	insert the (green) seal 2 into the head cover* place	H	2	H or R	0.38	H or R	V.A.	H or R	H
O36	put the head cover* in the manual press	H or R	3	H or R	0.39	H or R	N.V.A.	R	R
O37	press the (green) seal 2 in the head cover* place	H	3	H or R	0.36	H or R	V.A.	H or R	H
O38	place the ASS-5 on the worktable	H or R	2	H or R	0.28	H or R	N.V.A.	R	R
O39	pick the ASS-3	H or R	2	H or R	0.17	H or R	N.V.A.	R	R
O40	place the ASS-3 on the ASS-4 (still in support "B")	H or R	2	H or R	0.52	H or R	V.A.	H or R	H or R
O41	pick the ASS-5	H or R	2	H or R	0.29	H or R	N.V.A.	R	R
O42	place the ASS-5 on the ASS-3	H or R	3	H or R	0.44	H or R	V.A.	H or R	H or R
O43(4x)	pick the tie-rod	H or R	**3**	R	0.21	H or R	N.V.A.	R	R
O44(4x)	insert the tie-rod into ASS-5 place	H or R	**3**	R	0.43	H or R	V.A.	H or R	R
O45	pick the screw driver	(/)	(/)	(/)	(/)	(/)	(/)	(/)	(/)
O46	set the screwdriver head (if it is necessary)	(/)	(/)	(/)	(/)	(/)	(/)	(/)	(/)
O47(4x)	screw the tie-rod	H or R	**3**	R	0.58	H or R	V.A.	H or R	R
O48	release the screwdriver	(/)	(/)	(/)	(/)	(/)	(/)	(/)	(/)
O49	pick the (piston rod) nut 2	H or R	3	H or R	0.38	H or R	N.V.A.	R	R
O50	insert the (piston rod) nut 2 on ASS-6	H	3	H or R	0.62	H or R	V.A.	H or R	H
O51	screw the (piston rod) nut 2 manually	H	3	H or R	0.42	H or R	V.A.	H or R	H
O52	pick the mesh	H or R	**4**	R	0.20	H or R	N.V.A.	R	R
O53	insert the mesh on ASS-6*	H	3	H or R	0.53	H or R	V.A.	H or R	H
O54	remove the final product from support "B"	H or R	2	H or R	0.44	H or R	N.V.A.	R	R
O55	arrange the mesh on the final product	H	3	H or R	0.40	H or R	V.A.	H or R	H
O56	place the final product into the box	H or R	3	H or R	0.29	H or R	N.V.A.	R	R

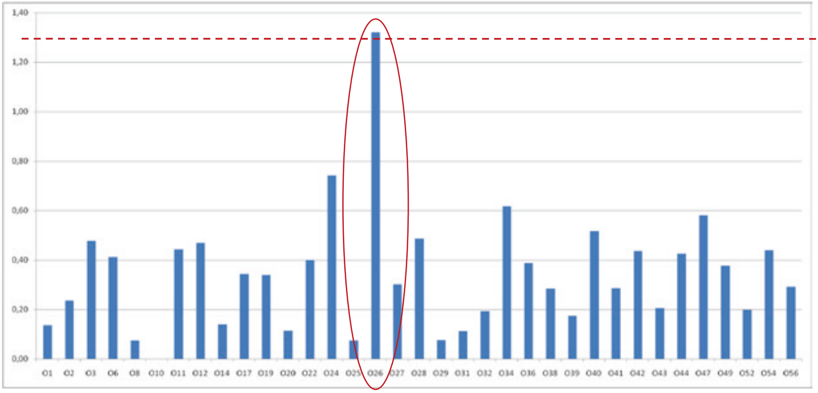

Fig. 12.13 CV value of tasks which could potentially be performed by the robot from a technical point of view

Table 12.13 Final task allocation logic according to the proposed framework and related examples

Technical evaluation result	Ergonomics evaluation result	Quality evaluation result	Economic evaluation result	FINAL RESULT	Task (example)
H	*irrelevant*	*irrelevant*	*irrelevant*	**H**	O4, O5, O7, O9 …
H or R	R	*irrelevant*	*irrelevant*	**R**	O6, O25, O43, O44 ….
H or R	H or R	R	*irrelevant*	**R**	O26
H or R	H or R	H or R	R	**R**	O11, O12, O19, O20 …
H or R	H or R	H or R	H or R	**H or R**	O2, O28, O40, O42 …

between the human and the robot will be useless and time-consuming. For this reason, it would be advisable for the operator to perform both tasks. This concept is summarized in Table 12.14.

12.5 Discussion and Hypothesis for Future Work

The following section aims to critically analyze the proposed approach in order to identify the main method critical issues for future developments and to investigate the main possibilities and innovations for collaborative assembly.

Table 12.14 Examples of task unification according to the use of resources

Task	INVOLVED COMPONENTS	FINAL RESULTS – task	FINAL RESULTS - activity
O1 - pick the piston rod	**piston rod**	**R**	**R**
O2 - insert the piston rod in the support "A"		**H or R**	
O3 - pick the o-ring	**o-ring**	**H or R**	**H**
O4 - place the o-ring on the piston rod		**H**	

12.5.1 Task Allocation Methodology: Future Developments

a. **Inclusion of dynamic task allocation methodologies for tasks which are classified as "H or R"**

The dynamic task allocation will be a core part of future collaborative workstations. In fact, a system where the operator can choose in real time and indiscriminately which task will be the next one according to his/her needs and wants could significantly improve cognitive ergonomics conditions, operators' psychological well-being, and production flexibility. Of course, this would be the perfect implementation of a human-centered design in the Industry 4.0 context. For this reason, it would be useful to add this possibility to future workstation development. Nevertheless, it is necessary to firstly identify which tasks of a sequence can be efficiently performed both by humans and robots by consider the real technical limitations of the robot system.

b. **Development of a multi-gripper technical evaluation**

The ability to properly pick up and manage a component strictly depends on the type of gripper which is intended for use for assembly activities. For this reason, it will be useful to further develop the proposed methodology by including multi-criteria evaluation of different kinds of gripper types in order to identify which one is the best solution for a certain assembly sequence. In this context, a recommended solution will be the development of a technical parameter which quantifies the percentage of success (in terms of robot usage) for a certain task according to the selected gripper type.

c. **Use of a more specific methodology for physical ergonomics evaluation (i.e., OCRA)**

The methodology for physical ergonomics evaluation proposed in this work is RULA. The selected method is simple and quick to use for different kinds of industrial applications. Nevertheless, this methodology presents some limitations especially because it does not consider in detail the tasks, workloads, and repetitions. For this reason, the RULA method is suggested for use for a preliminary postural evaluation; further investigation of the situations with dedicated approaches (i.e., NIOSH for lifting and carrying, Snook and Ciriello for the whole-body pushing and pulling, OCRA for the handling of low loads at high frequency..) is recommended for a proper physical ergonomics analysis.

d. **Integration of cognitive ergonomics considerations**

The sharing of workspaces and the physical interaction between humans and industrial robots could affect the cognitive ergonomics of the collaborative work. In this context, it would be mandatory to minimize mental stress and psychological discomfort, which could arise during hybrid operations. In fact, even if safety measures are well designed and implemented, the presence of the robot must not be perceived as a hazard or as a source of stress for humans. Designers should consider these kinds of cognitive ergonomics problems in order to develop anthropocentric and human-friendly collaborative workstations also from a psychological point of view.

e. **Inclusion of a method for the new assembly cycle definition according to the calculated task allocation**

Finally, the last consideration concerns the development of a quick and structured procedure for the new assembly cycle definition according to the planned task allocation. In this case, a new sequence should respect the defined human–robot task division and provide useful information for the design of the layout of the new collaborative workcell. The new cycle data should also support the designers in the comparison between the production performance of the actual and future workstation, in order to offer a clear overview of the costs and benefits that the introduction of the collaborative robot can provide to the overall production system.

12.5.2 Real-Time Allocation for Assembly

One of the most interesting and challenging features of collaborative assembly is the real-time allocation of tasks and responsibilities between the robot and the human operator. In these situations, the robot may behave with its own agency, i.e., goal-oriented initiative. Such agency endows the robot with the ability to negotiate the task owner with the operator and the order of the tasks. Researchers have shown that providing a machine or robotic agent with autonomous capabilities yields important benefits for human–robot team fluency (Gombolay et al. 2017). Furthermore, such agency is the basis for the emergence of smart interaction patterns with continuously distributed tasks among all contributors. In fact, while there are capabilities unique to both machines and humans, there is also a natural overlap. The objective of task allocation is to achieve an optimal sharing of these capabilities. For the dynamic task allocation, it is necessary to create a model of the assembly process and the sensing capacity to endow the collaborative robot with sufficient situational awareness. In fact, correct real-time task allocation is only possible with a sufficiently accurate virtual twin of the system. Such a virtual twin will be the object of analysis of the task-sharing system in conjunction with the feedback from situational awareness. Task allocation may be modified online by communication (verbal, nonverbal), by operator initiative or by another change in the system state. As can be seen, the dynamic task allocation problem is characterized by a degree of unpredictability. Such kinds of environments are called unstructured. Even in the simplest environment, the design of such interactions is not easy. All the challenges of motion planning in a dynamic environment are combined with the task allocation problem. This results in a combination of geometrically constrained motions in the space and ordered sequences of discrete tasks. For this reason, real-time task allocation problems are best modeled as hybrid systems. On the one hand, the task is part of a sequence of discrete states best modeled as a discrete event system (DES). Such a system evolves from the actual state in an undeterministic way due to the action of the operator. On the other hand, the motions executed by the robot are defined by the executed task and the traditional constrains of human–robot physical interaction. Such a combination of a DES with a motion planning system is called a hybrid system. Observe that this topic is characteristic for the fourth industrial revolution. Including the human operator as a CPS and making possible the dynamic integration of humans and machines, the coordination and orchestration of the smart factories become pervasive. This is only possible thanks to the correct integration of the required systems. In fact, the integration of heterogeneous digital systems is a must. In particular, advanced visual sensing systems must share high-structured information between CPS using the correct communication channels. Among these channels, physical contact may also be used to create an interaction interface and convey information to CPS. Traditionally, such problems have been attacked via high-level task planning where a sequencing of task sequences is computed to lower-level planning to compute the motions for the arm (Pellegrinelli et al. 2017). Initial research in task allocation perceived that, while there are capabilities unique to both machines and humans, there are also overlapping capabilities that provide the opportunity to variably assign tasks in accordance with resource availability (Ranz et al. 2017). Other systems based on Artificial Intelligence are based on a learning framework to construct an optimal task-sharing schedule. In works like Munzer et al. (2017) and Mitsunaga et al. (2008), the authors propose an online learning algorithm which adapts to the operator behavior during the task-sharing procedure. Given an initial task schedule, it is possible to adapt the robot's actions based on comfort and discomfort measurements gathered from the sensing system. Other approaches leverage the fact that people act not only as a response to external or internal stimuli, but also in order to achieve goals to design algorithms capable of predicting the intended actions of the operator in order to perform the task allocation (Demiris 2007). This is a feasible alternative to communication to understand the intentions in real time.

12.5.3 Cell Digitalization

We have already discussed how a collaborative robot can be introduced inside a manufacturing cell to simultaneously improve the cell's productivity and reduce the operator's strain. To this end, we have identified and allocated the optimal set of tasks that a collaborative robot can execute. Our approach, however, presents two fundamental limitations:

- Manual synchronization between the operator and the robot to conclude the assembly sequence
- The robot can only execute its allocated tasks in a predefined sequence.

Both limitations result from the fact that our approach only exploits static information or knowledge of the assembly process known a priori. Indeed, to allow higher levels of flexibility like dynamic task allocation, autonomous reaction, and adaption to unexpected situations, etc., it is necessary to enrich the "situational awareness" of the robot and to endow it with an autonomous or semi-autonomous decision-making mechanism. In other words, full cell digitalization in smart factories not only involves delegating known tasks to robots but also endows them with proper perceptive, cognitive, and control mechanisms for real-time monitoring and adaptation during the execution of the assembly process. The rest of the section is devoted to briefly introducing different technologies and approaches found in the state of the art to improve the situational awareness of the robot, including operator monitoring, and different inference mechanisms allowing autonomous adaptation during the assembly process.

12.5.4 Situational Awareness

The first step to increase the situational awareness of the robot is to provide it with some means of perception, not only to perceive the surrounding environment but also to measure its own internal states and to monitoring the operator's activities. Therefore, such means of perception cannot be defined only in terms of raw measurements of the physical world (e.g., provided by laser scanners, RGB cameras, RGB-D sensors, inertial measurement units, encoders, torque sensor, etc.) but also in terms of interactive HMI allowing bidirectional and natural information flows between the operator and the robot. This evolution from raw measurements to information flows defines the second step: understanding of the current situation, which includes the environment, robot, operator, and manufacturing process states. The third and last step consists of the prediction of future situations.

Key HMI interfaces in Industry 4.0 are the *automatic speech recognition*, the *gesture recognition*, the *enhanced reality* (either in terms of *augmented reality* or *virtual reality*), *physical HRI,* and the *prediction of operator's intentions* (Ruiz Garcia et al. 2019):

- *Automatic speech recognition* consists of the identification and recognition of patterns bearing the information content inside the speech waveform (O'Shaughnessy 2008). Although speech represents the most efficient method of human interaction, Lotterbach and Peissner (Lotterbach and Peissner 2005) state that voice user interfaces cannot represent a replacement for a classical graphic user interface (GUI) but can complement to them, so that under certain conditions and in certain contexts, they provide the most comfortable and efficient method of interaction.
- A gesture is defined by any expressive body motion capable of transmitting meaningful information to other entities in the workspace. Nowadays, thanks to the advent of RGB-D sensors, visual *gesture recognition* is one of the most widely used methods in the industry (Sansoni et al. 2009). A comprehensive review of applications and technologies can be found in Mitra and Acharya (2007).
- *Enhanced reality* consists of the enrichment of perceptive measurements of the physical world with digital information superimposed on top of it (Craig 2013).
- *Physical contact detection*, isolation, and reaction have been extensively explored in the robotics community, especially in the field of collaborative robotics (Haddadin et al. 2012; Ajoudani et al. 2018)

where the contact between the robot and the operators is expected to be frequent.

- *Prediction of operator's intentions* relies on monitoring techniques (Pirri et al. 2019; Mauro et al. 2018, 2019) and allows the enhancement of the effectiveness of collaboration between robots and humans, especially in industrial scenarios where safety greatly depends on the understanding between humans and robots.

12.6 Conclusions

HRC is a primary cyber-physical technology in Industry 4.0. There is no doubt that the global market of industrial collaborative robotics is extensively and continuously growing. It is reasonably possible to suppose that collaborative assembly will be a crucial application in the near future. This chapter aims to explain the main concepts about the introduction of industrial collaborative robots into manual assembly systems. The contents gave a general overview of the main features and requirements of human–robot collaborative assembly in the context of Industry 4.0, and discussed the opportunities and problems related to its design procedure. The main objectives of the adoption of collaborative systems into traditional manual assembly workstations is to improve operators' work conditions and production performances by combining inimitable human ability with smart machines' strengths. The main specific outcomes of this chapter based on Industry 4.0 applied to SMEs are:

- Identification of the main parameters for the possible adoption of collaborative systems into the assembly process
- Development of a structured framework for the evaluation of the technical possibility to use a collaborative robot for assembly activities
- Implementation of a multi-criteria method for human–robot task allocation in assembly activities by considering technical, ergonomic, organizational and economic principles
- Creation of the basis for the development of a digital tool for a guided self-evaluation.

In general, the proposed approach is based on hierarchical task allocation, which is able to define if a task can be performed efficiently by the operator (H), by the robot (R), or by both indiscriminately (H or R). The core part of that method is the technical evaluation, which analyzes if a generic feeding, handling or assembly task can be performed efficiently by a robot by using a proper amount of production resources in a suitable time according to product and process critical issues. The proposed methodology enables SMEs to carry out a preliminary feasibility analysis of the collaborative process. In the future, this methodology will be used as a basis for developing a digital tool for supporting SMEs technicians to self-evaluate the potential of collaborative systems in assembly processes. Such an application will help SMEs to a proper use of industrial collaborative robots and as a result, to improve assembly performances, operators' work conditions, and production quality. The chapter also introduced the SMF laboratory of the Free University of Bolzano-Bozen and explained how to apply intuitive HRI for assembly purposes through the description of a laboratory case study in a realistic industrial lab environment. For the proposed case study, a Universal Robot model UR3 equipped with a 2-finger Robotiq collaborative gripper is used for the collaborative assembly of a medium-size pneumatic cylinder. Finally, the current work in progress and future hypotheses for improvement are introduced and discussed by investigating the main possibilities and innovations for collaborative assembly.

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