The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-021-06653-y

ORIGINAL ARTICLE

Methodology for the definition of the optimal assembly cycle and calculation of the optimized assembly cycle time in human-robot collaborative assembly

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Received: 18 August 2020 / Accepted: 18 January 2021

Abstract
Industrial collaborative robotics is an enabling technology and one of the main drivers of Industry 4.0 in industrial assembly. It allows a safe physical and human-machine interaction with the aim of improving flexibility, operator's work conditions, and process performance at the same time. In this regard, collaborative assembly is one of the most interesting and useful applications of human-robot collaboration. Most of these systems arise from the re-design of existing manual assembly workstations. As a consequence, manufacturing companies need support for an efficient implementation of these systems. This work presents a systematical methodology for the design of human-centered and collaborative assembly systems starting from manual assembly workstations. In particular, it proposes a method for task scheduling identifying the optimal assembly cycle by considering the product and process main features as well as a given task allocation between the human and the robot. The use of the proposed methodology has been tested and validated in an industrial case study related to the assembly of a touch-screen cash register. Results show how the new assembly cycle allows a remarkable time reduction with respect to the manual cycle and a promising value in terms of payback period.

Keywords Human-robot interaction · Collaborative assembly · Collaborative robotics · Assembly cycle · Industry 4.0

1 Introduction and motivation

Industry 4.0, or the so-called "Forth Industrial Revolution" [1], is the reaction of production companies to the even more demanding requests of global markets for flexibility and productivity in terms of lot sizes, variants, and time-to-market. One of the main enabling technologies of this revolution is industrial collaborative robotics [2]. Collaborative robots (or cobots) are cyber-physical systems (CPS) which allow the implementation of human-robot interaction (HRI) or collaboration (HRC) by realizing a physical and safe sharing of workspaces during manufacturing tasks [3, 4]. The aim is to simultaneously enhance the operator's occupational conditions and the production performance of the company by combining the potential of robotics with human skills. In this regard, the use of HRC in the assembly will be one of the most interesting and promising applications.

Industry 4.0 and related technologies are introducing new opportunities but also new challenges. According to [5], the current maturity level of Industry 4.0 concepts is generally low, especially in small and medium sized enterprises (SMEs). Collaborative robotics is perceived as a "must have" and high-potential technology which requires a great effort and a long-term strategy to be properly implemented. In addition, a large part of companies (especially SMEs) does not have in-house know ledge and skills about this technology, even if experts in the field support the relevance for the growth of their business [6].

For these reasons, it is necessary to provide methodologies and tools with which companies are familiar to promote a quick and easy adoption of collaborative robotics in assembly. This will be essential to overcome the difficulties and the technological barriers related to the effective and efficient integration of HRI in manufacturing companies. In particular, in

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addition to the crucial topics of safety and ergonomics, the definition of the assembly cycle is fundamental in the design of collaborative systems, especially for complex assemblies. Given a certain allocation of tasks between the human and the robot by considering the product and process main features, this involves the collaborative task scheduling according to technical as well as economical requirements.

This article is organized as follows. After the introduction and motivation provided in Section 1, Section 2 provides a literature review about the topic and related research questions. Section 3 deals with the development of the methodology for the design of human-centered and collaborative assembly systems starting from manual assembly workstation, particularly focusing on the definition of the optimal collaborative assembly cycle and to the preliminary feasibility evaluation. Section 4 presents the application of the abovementioned approach by means of an industrial case study. Finally, the discussions and conclusions are summarized in Section 5 and Section 6 respectively.

2 Literature review

Following, a summary of the main research works related to the design of human-robot assembly systems particularly focusing on the definition of a collaborative assembly cycle is provided.

The following works related to different methodologies for the planning of HRI tasks and for the development and balance of collaborative assembly systems. Çil et al. [7] proposed a mixed-model assembly line balancing problem with the collaboration applied to HRC. Weckenborg et al. [8] investigated the assembly line balancing problem with collaborative robots using a mixed-integer programming formulation. Xu et al. [9] developed a HRC planning for re-manufacturing purposes by implementing an optimized disassembly sequence. Cheng et al. [10] proposed a framework which enables the robots to adapt their actions to the human's work plan by integrating collision avoidance. Mateus et al. [11] presented an algorithm for the identification of assembly task precedence by splitting the products into sub-assemblies. Zhang et al. [12] developed a deep learning–based method to forecast the operator's motion for online robot action planning and execution in assembly. Fager et al. [13] presented a mathematical model for the estimation of the cycle time associated with cobot-supported kit preparation. Mateus et al. [14] provided a methodology for information extraction and processing and collaborative assembly solution generation and evaluation. Malik and Bilberg [15] proposed an assessment method of assembly tasks based on the physical features of the components and associated task description. Herfs et al. [16] simplified the commissioning of HRC processes by combining product-lifecycle-management with collaboration-specific process planning. Rahman and Wang [17] presented a two-level feedforward optimization strategy that determines optimum subtask allocation before the assembly starts. Jungbluth et al. [18] presented software based on product model used to propose a disassembly plan by developing an intelligent robot assistant. Gabler et al. [19] provided a framework based on game theory that allows robots to choose appropriate actions with respect to the action of a human. Faber et al. [20] developed an optimal assembly sequence planner by using a complete assembly graph of the final product as well as the ergonomic conditions. Faber et al. [21] introduced criteria for assigning assembly steps to the human or the robot by presenting a risk model applied to the planning of assembly sequence.

In addition, the following works investigated more in detail the design of the HRI in terms of assembly system and collaborative workspace. Gualtieri et al. [22] presented a case study research for the design of a collaborative workstation to improve the operators' physical ergonomics while considering productivity. Malik et al. [23] explored the design of human-centered production systems by using virtual reality and developed a unified framework for its integration. Tang et al. [24] compared the cycle time, waiting time, and operators' subjective preference in collaborative assembly when different handover prediction models were applied. Hanna et al. [25] analyzed the challenges with current planning and preparation processes for the final collaborative assembly. Lemmerz et al. [26] developed an overall simulation tool for the design of collaborative assembly systems. Malik and Bilberg [27] proposed a digital twin framework to support the design, build, and control of human-machine cooperation for assembly works. Malik and Bilberg [28] presented a systematic framework for the deployment of cobots in existing assembly cells for enhanced productivity.

According to this overview, different aspects related to the design of HRC in assembly have been studied. Nevertheless, an all-encompassing and structured methodology for the design of collaborative assembly workstations starting from manual ones, which also considers the different possibilities in terms of human-robot task allocation, has not been extensively investigated. In particular, an intuitive and simple methodology for a static assembly cycle definition and scheduling based on tools, with which companies are familiar is missing. A further crucial point is the lack of a methodology capable of taking into account also the economic aspects of HRI as a production and assistance system.

As a consequence, we want to draw attention to these needs by answering the following research questions:

> RQ1: How to develop a systematical methodology for the design of human-centered and collaborative assembly systems starting from manual assembly workstation?
> RQ2: How to schedule the collaborative assembly cycle by considering the product and process main features as well as a given task allocation between the human and the robot?
> RQ3: How to find the best solution from the economic point of view?

3 Development of a systematic methodology for the design of human-centered and collaborative assembly systems

In this section, we present the developed methodology for the design of collaborative and human-centered assembly systems starting from an existing manual assembly situation. The proposed methodology is mainly addressed for the evaluation of assembly systems with smaller lot sizes and originally manual assembly processes. The methodology is divided into six sequential steps (see Fig. 1). In Sections 3.1–3.6, all single steps are described in detail.

3.1 Analysis of the current situation

The first step of the proposed methodology is the detailed analysis of the manual assembly system (current situation). This requires the collection of different input data about the assembly process. The methodology is structured in such a way as to use common and easy to collect data. The main required inputs are:

- Assembly cycle features (sequence of tasks, priority, assembly priority chart);
- Average assembly task time;
- Average labor cost.

3.2 Allocation of assembly tasks between the human and robot

The second step of the methodology aims to allocate the tasks between the human and the robot. This involves the analysis of the current manual tasks and the consideration of the potentials and limitations of both the human and the robot. The allocation of tasks might require additional data with respect to step 1 according to the company's needs and objectives. The main guidelines for a preliminary evaluation are summarized in Table 1 [29, 30].

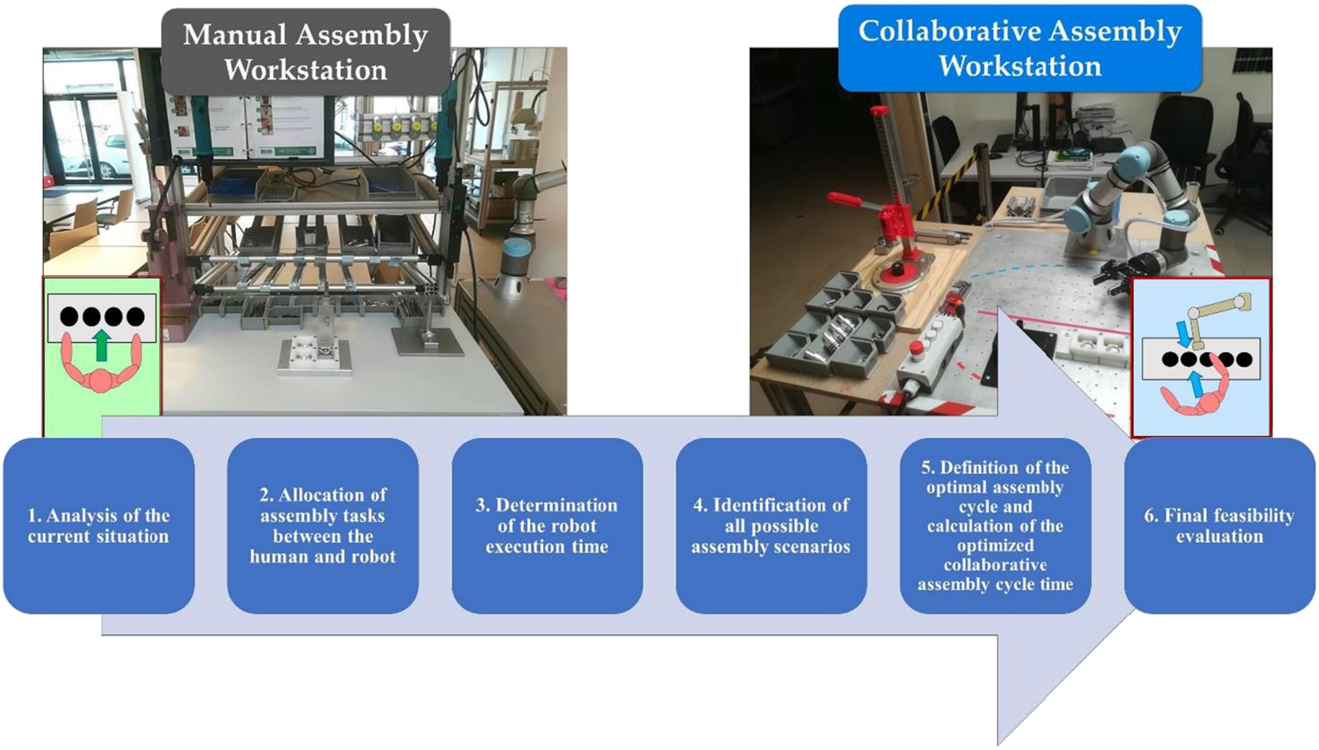


Fig. 1 Overview of the six steps in the systematical methodology for the design of collaborative and human-centered assembly systems

Table 1 Main guidelines for the preliminary evaluation of human and robot task allocation starting from manual activities [29, 30]

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 low task valorization	Activities which imply high handling ability and dexterity
Not Value Adding (NVA) activities	Value Adding (VA) activities
Activities which require standardization and/or quality improvements	Activities which imply flexibility and ability to adapt

According to the so-called Human-Robot Activity Allocation (HRAA) algorithm developed by Gualtieri et al. [29, 30], the current assembly cycle has to be divided into single manual tasks. A task(*i*) can be classified according to the most suitable resource to be performed by using a so-called Final Evaluation Index (*FEI(i)*). For each task, this index aims to define the best allocation according to the analysis of product and process features related to technical issues, ergonomics, quality, and economics. There are four *FEI(i)* possibilities [31]:

- Task(*i*) performed exclusively by the operator (*FEI(i)* = “H”);
- Task(*i*) performed exclusively by the robot (*FEI(i)* = “R”);
- Task(*i*) performed equally by the operator or robot (*FEI(i)* = “H or R”);
- Task(*i*) performed by the operator with the help of the robot (*FEI(i)* = “H + R”).

3.3 Determination of the robot execution time

Before proceeding with the analysis of the various possible scenarios, it is firstly necessary to estimate the execution time for the tasks which are allocated to “R,” “H or R,” or “H+R.” In fact, it will not be possible to calculate the overall cycle time without knowing the time that is needed for a collaborative robot to perform a certain task, which originally was performed by an operator manually. According to the desired accuracy of the output data and to the availability of time for the design, the methodology proposes two parallel solutions:

1. Definition of the robot execution time by using a digital model of the assembly task through a dedicated simulation software (digital twin);
2. Estimation of the robot execution time by modifying the detected manual assembly time through specific coefficients.

In the former case, the data are computable by using dedicated simulation software for HRI such as Tecnomatix Process Simulate from Siemens [32]. This requires the creation of a digital model of the robotic task and the calculation of the task time by running the related simulation in the virtual environment. In the latter, for all the tasks that are potentially executable by a robot, the robot time will be estimated by properly changing the measured manual assembly time using specific coefficients. These are defined as C_1 and C_2 and aim to change the measured manual task time according to the *FEI(i)* index. According to [8], for a preliminary assessment, it is possible to use the values introduced in Table 2. In particular, $t(i)_R$ is defined as the expected robot execution time for a task(*i*) which is potentially executable by a robot (*FEI(i)* = “R” or “H or R”) and it is related to C_1. It is assumed that the time needed for a possible change of the robot end-effector is included in that estimation. On the other hand, $t(i)_{H+R}$ is the expected execution time of a collaborative operation (*FEI(i)* = “H+R”) and it is related to C_2. Finally, for a task(*i*) which is supposed to be performed by a human (*FEI(i)* = “H”), the expected execution time $t(i)_H$ is considered equal to the current (measured) time. Referring to $t(i)_H$, even if there could be small changes in carrying out the same activities, it is assumed that the execution time in the new assembly cycle will be comparable to the one detected in the current one. For this reason, the proposed values of $t(i)_H$ are the same as the measured.

There is no doubt that the simulation approach will be more complex and time-consuming with respect to the coefficient-based approach. Nevertheless, the output data will be more accurate and reliable. Therefore, the presented methodology

Table 2 Estimation of the robot $t(i)_H$ and collaborative $t(i)_{H+R}$ task execution time [8]

HRAA algorithm results	Relationship between manual and robotic execution task time	Coefficient value
FEI(i) = “R”; FEI(i) = “H or R”	$t(i)_R = C_1 * t(i)_H$	$C_1 = 2$
FEI(i) = “H + R”	$t(i)_{H+R} = C_2 * t(i)_H$	$C_2 = 0{,}7$

should be used for a preliminary assessment of the possibility to use collaborative solutions in assembly before investing time and human resources in a more detailed simulation. For such a preliminary check, high-quality input data are not essential. Therefore, the choice between the two methods of calculation depends mainly on the stage of investigation (preliminary or detailed study).

3.4 Identification of all possible assembly scenarios

The fourth step of the proposed methodology is the identification of assembly scenarios (or alternative assembly sequences). In fact, for those tasks that are allocated to human or robot (*FEI(i)* = "H or R"), it is possible to have different alternatives depending on how the human or the robot are intended to be used during the assembly. A static approach is applied in this work. In this case, the task allocation is strictly defined by the assembly cycle and the operator cannot choose in real time and indiscriminately which task allocated to "H or R" will be the next one according to the operator's needs (dynamic task allocation) [30]. Basically, the number of possible collaborative assembly sequences or "scenarios" (M) to be evaluated depends on the number of tasks that are allocated to "H or R" (N). The relationship between these two variables can be modeled as an exponential growth (see Eq. (1)):

$$M = 2^N \text{ (scenarios)} \tag{1}$$

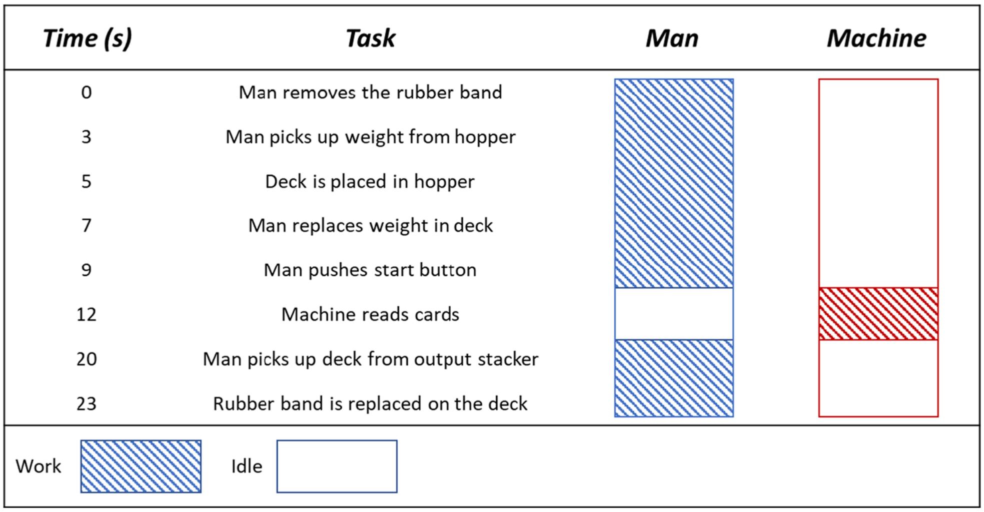
Considering the fact that with N the value of M rises exponentially, the complexity of the problem and the time required for the analysis of the alternatives increase accordingly.

3.5 Definition of the optimal assembly cycle and calculation of the optimized collaborative assembly cycle time

The fifth step of the methodology is the study of the optimal assembly cycle between all the possible scenarios identified in step 4. This refers to a human-robot task scheduling problem. An optimization of the static collaborative assembly sequence based on the minimization of the overall assembly cycle time is proposed. This has to be done in consideration of the assembly constraints and priority chart by implementing the corresponding optimized man-machine (robot) chart for each of the possible scenarios. A man-machine chart (MMC) is a graphical representation of the simultaneous activities of workers and machines. MMC is a generic and widely used term that in no way supports discrimination against female operators. Basically, it represents the periods of cooperative work, independent work, and idle time along a time scale. Each of the idle times would be examined for the possibility of reducing or eliminating it, thus resulting in a revised distribution of work and an optimized MMC [33]. The improved distribution of the work will be the basis for the definition of the new collaborative assembly cycle. The reason to use an optimization approach based on the use of MMCs is related to the familiarity, intuitiveness, and simplicity that this tool presents to users of manufacturing companies and especially SMEs [34]. An example is provided in Fig. 2.

The computation of the optimized assembly cycle time according to the optimized MMC for a certain scenario ($Tc_{tot}(m)^*$) is provided in Eq. (7). The computation of the best assembly cycle time among all scenarios ($Tc_{opt}(M)$) is provided in Eq. (8). The parameters and the equations needed for the calculation of $Tc_{tot}(m)^*$ and $Tc_{opt}(M)$ are presented in Table 3. In addition, for the calculation of the equations presented in

Fig. 2 Example of man-machine multiple activity chart for reading a deck of cards in a card reader (adapted from [35])



Time (s)	Task	Man	Machine
0	Man removes the rubber band	▨	☐
3	Man picks up weight from hopper	▨	☐
5	Deck is placed in hopper	▨	☐
7	Man replaces weight in deck	▨	☐
9	Man pushes start button	▨	☐
12	Machine reads cards	☐	▨
20	Man picks up deck from output stacker	▨	☐
23	Rubber band is replaced on the deck	▨	☐

Work ▨ Idle ☐

Table 3 Parameters and equations for the calculation of $Tc_{tot}(m)^*$ and $Tc_{opt}(M)$ referring to the optimized MMC

Parameter	Unit	Description	Equation
m	/	Assembly sequence to be evaluated (scenario) according to the MMC	
M	/	Set of possible collaborative assembly sequence to be evaluated (scenarios)	$M = \{m = 1, \ldots, n\}$
i	/	Sequential or parallel task $\in I$	
I	/	Set of all the tasks needed for the assembly	$I = \{i = 1, \ldots, n\}$
a	/	Assembly activity which is defined as the interval in which two parallel tasks $\in I$ with $FEI(i)$ = "R" and FEI(i) = "H" (respectively) are completed	
A	/	Set of all assembly activities needed for the assembly	$A = \{a = 1, \ldots, n\}$
$t(i)_H$	[s/pcs]	Average execution time of task $i \in I$ with $FEI(i)$ = "H" (measured time of the current manual assembly)	
$t(i)_R$	[s/pcs]	Average execution time of task $i \in I$ with $FEI(i)$ = "R“	
$t(i)_{H+R}$	[s/pcs]	Average execution time of task $i \in I$ with $FEI(i)$ = "H+R"	
ta	[s/pcs]	Average assembly activity time, which is defined as the maximum execution time between two parallel tasks $\in I$ with $FEI(i)$ = H and $FEI(i)$=R (respectively) for a certain activity $\in A$	$ta=\max\{t(i)_H;t(i)_R\}\,\forall i \in a$ (2) If $t(i)_R=0$ $ta=t(i)_H$ If $t(i)_H=0$ $ta(i)=t(i)_R$
$T_H(m)$	[s/pcs]	Total operator execution time for the execution of a sequential or parallel set of tasks $\in I$ with $FEI(i)$ = "H" of a certain scenario $m \in M$	$T_H(m) = \sum_{i=1}^{I} t(i)_H$ (3)
$T_R(m)$	[s/pcs]	Total robot execution time for the execution of a sequential or parallel set of tasks $\in I$ with $FEI(i)$ = "R" of a certain scenario $m \in M$	$T_R(m) = \sum_{i=1}^{I} t(i)_R$ (4)
$T_{H+R}(m)$	[s/pcs]	Total collaborative execution time for the execution of a sequential or parallel set of tasks $\in I$ with $FEI(i)$ = "H+R" of a certain scenario $m \in M$	$T_{H+R}(m) = \sum_{i=1}^{I} t(i)_{H+R}$ (5)
$Ta(m)$	[s/pcs]	Total execution time of all activities of a certain scenario $m \in M$	$Ta(m) = \sum_{a=1}^{A} ta$ (6)

Table 3, for Eq. (7) and for Eq. (8), the following assumptions are introduced:

- Only one operator and one collaborative robot are used for the execution of the assembly in a single workstation;
- Parameters are deterministic;
- $t(i)_R$ and $t(i)_{H+R}$ are estimated according to the indications of Table 2;
- For the definition of the MMC, if there are several parallel tasks with the same $FEI(i)$, it is assumed that the operator and the robot can perform only one task at a time. This means that parallel tasks that have not yet been performed will be executed sequentially as soon as possible. For this reason, it is possible to have at least a task(i) with $FEI(i)$ = "H" and a parallel one with $FEI(i)$ = "R."
- Parameters are related to the analysis of the optimized MMC (which derives from the "original" MMC). For each possible scenario, the optimized MMC is the one obtained from the analysis of the assembly cycle by properly redistributing the work between the operator and the robot in order to minimize the assembly cycle time.
- The optimized MMC is based on the possibility to reduce the assembly time by performing in the downtime of the current/analyzed cycle (i.e., "Cycle K") some tasks with $FEI(i)$ = "H" foreseen for the next cycle (i.e., "Cycle K+1"). This is possible in accordance with the task execution time, task priority, and $FEI(i)$. It is assumed that this chance is only possible for the operator and not for the robot, since high flexibility and adaptability are required. In addition, it is assumed that a single task with $FEI(i)$ = "H" can be performed intermittently, which means that it can be divided into sub-tasks and performed at different times.

Following, Eq. (7) and Eq. (8) are presented for the calculation of $Tc_{tot}(m)^*$ (for a certain scenario $m \in M$) and $Tc_{opt}(M)$:

$$Tc_{tot}(m)^* = Ta(m) + T_{H+R}(m) \qquad [\mathrm{s/pcs}] \tag{7}$$

$$Tc_{opt}(M) = \min\left\{Tc_{tot}(m)^*\right\}\forall m \in M \qquad [\mathrm{s/pcs}] \tag{8}$$

3.6 Final feasibility evaluation

The last step is the final economic feasibility analysis. This means to evaluate which of the identified scenarios is the most profitable from an economic point of view. In fact, it is not always certain that the scenario with the greatest assembly time reduction is also the most convenient one. This is because some implementation and operative costs can vary according to the single scenario (i.e., the number and type of end-effectors) and can cancel the economic advantage obtained by reducing the cycle time. To perform such an analysis, the payback period (PBP) as the main key performance indicator (KPI) is proposed. Basically, it is the time period needed to recover the cost of an investment. It is defined as the ratio between the costs for an investment and the relative net profits achievable through that investment over a time period. It is often used to quantify the effectiveness of an investment or to compare the benefits of multiple different investments. In this regard, *PBP(m)* is the PBP for a certain scenario $m \in M$. (see Eq. (9)). The best solution among the various scenarios (*PBP(M)*) will be the one with the lowest PBP value (see Eq. (10)).

$$PBP(m) = \frac{Costs\ of\ Investments}{Net\ Profits} \qquad [\text{years}] \qquad (9)$$

$$PBP(M) = \min\{PBP(m)\} \qquad [\text{years}] \qquad (10)$$

An important aim of industrial HRI is the improvement of operator's work conditions by designing human-centered and collaborative solutions [36]. For this reason, in the case the collaborative robot will be used as a physical or cognitive assistance system, it is possible to consider the related investments also as investments for occupational health and safety (OHS). In order to integrate the classical calculation of the PBP with the contribution of the investments related to OHS, it is assumed that the benefits against the costs provide a return on prevention (ROP) with a factor of 2.2 [37]. In practice, this means that for 1 Euro (per employee per year) invested by a company on OSH, it is expected a potential economic return of 2.2 Euros. For this reason, the economic return related to OHS investments could be considered a part of the achievable net profits.

After explaining the proposed methodology, Section 4 presents its application in a real industrial case study. This case study has been used to validate the practical applicability of the methodology and to identify strengths and weaknesses of the method.

4 Industrial case study: assembly of touch-screen cash registers

The assembly of a large touch-screen cash register is the subject of the industrial case study used to validate the proposed methodology. The company is an SME located in Eastern Europe and produces cash registers for retail as well as special electronic devices for particular applications such as automotive, healthcare, and nuclear. The assembly is composed of 35 manual tasks grouped in 16 macro-phases. The average assembly cycle time is 7.506 [s/pcs]. More details about production data are exposed later in Table 4. For reasons of confidentiality, some of the data in the following sections do not represent the real values. Nevertheless, the assumed data are in line with reality and do not affect the reliability of the result and the effectiveness of the proposed methodology.

4.1 Analysis of the current situation

Table 4 summarizes the main input data of the methodology about the current assembly cycle according to step 1 indications. The table introduces the concept of "priority," which is represented by one or more previous tasks (task (*i-1*)) that must necessarily be completed before performing the analyzed task (task(*i*)).

4.2 Allocation of assembly tasks between the human and robot

For each task(*i*) of Table 4, the corresponding *FEI(i)* value is calculated according to Section 3.2. Table 6 summarizes the results.

As an example, task(1) will be approximately evaluated in Table 5 according to the guidelines presented in Table 1. It is important to underline that the allocation of tasks is a crucial part of the methodology and therefore it is necessary to carry it out with particular care. The following example is just a simplified analysis for clarification purposes.

Results show that there are 22 tasks with *FEI(i)* = "H", 11 tasks with *FEI(i)* = "R," and two tasks with *FEI(i)* = "H or R." The assembly priority chart (according to the results of Table 6) is presented in Fig. 3. Usually, the execution of multiple assembly tasks by a robot requires different end-effectors. In our case study, the tasks are related to common activities like (1) cleaning, (2) screwing, (3) laying/fixing of materials, and (4) general assembly (possible with a gripper). For this reason, the potential number of required end-effectors is four. Some will be purchased while others can be integrated into the robot system by using existing tools with a minimum effort. This has to be considered later in the detailed design and the economic evaluation of the collaborative workcell costs for the PBP calculation.

4.3 Determination of the robot execution time in the case study

In this work, the estimation of the robot execution time $t(i)_R$ is provided by using the coefficients as the aim of the case study was to perform a preliminary analysis. Following, $t(i)_R$ for tasks with *FEI(i)* = "R" or *FEI(i)* = "H or R" is calculated by using C_I=2 according to Table 2. Due to the fact that there are no tasks with *FEI(i)* = "H+R", the calculation of $t(i)_{H+R}$ is not included/necessary in this analysis. Table 7 provides the estimation of $t(i)_R$ for the analyzed case study.

Table 4 Main input data

Main phase	Task (i)	Task name	Priority	$t(i)_H$ (s)
1	1	Cleaning of internal frame perimeter surface	0	4
	2	Internal perimeter adhesive labeling	1	34
	3	Frame cables preparation	2	40
2	4	Removing of protective screen film	0	8
	5	Internal perimeter adhesive labeling	4	150
	6	2x metal bracket assembly (2x small screws and washers for each bracket)	5	75
	7	Positioning of protective screen film	6	8
3	8	Removal of perimeter adhesive labels (frame)	3 ; 7	30
	9	Removal of perimeter adhesive labels (screen cover)	8	25
	10	Insertion of screen cover	9	23
	11	Assembly manual crushing	10	9
	12	Internal cables preparation	11	31
4	13	Laying of silicone on the cover group assembly perimeter	12	92
	14	Cleaning of perimeter	13	36
5	15	Electric parts and support assembly (lower case part)	0	2640
6	16	Electric parts assembly (cover group part)	14	1800
7	17	Screen cleaning (paper and compressed air)	16	32
	18	Screen and cover group assembly	17	3
	19	Visual quality check	18	24
8	20	Cable insertion and arrangement	15; 19	100
	21	Final insertion and assembly	20	30
	22	Bar-code application, scan, and control	21	45
9	23	SW installation, configuration, quality check (real labor time)	22	300
10	24	Perimetral screws screwing (20x)	23	260
11	25	Perimetral cleaning	24	40
	26	Perimetral adhesive labeling (2x)	25	320
12	27	Perimetral rubber cover positioning and fixing	26	300
13	28	Cleaning of frontal zone	27	50
	29	Plate gluing and positioning (2x)	28	44
	30	UV glue fixing	29	324
	31	Central label positioning	30	20
14	32	Final screen cleaning (general and precision) and visual checking	31	390
15	33	Final perimetral refinement	32	50
16	34	Power supplier preparation	33	40
	35	Final packaging	34	129

4.4 Identification of all possible assembly scenarios

The results exposed in Table 6 show that the number of tasks which are allocated to "H or R" (*N*) is equal to two. These tasks are task(*13*) and task(*28*). Therefore, according to Eq. (1), the number of possible collaborative assembly sequences to be evaluated or "scenarios" (*M*) is four. Following, all possible scenarios are summarized:

- Scenario "*m1*": *FEI(13)* = "R" and *FEI(28)* = "R";
- Scenario "*m2*": *FEI(13)* = "R" and *FEI(28)* = "H";
- Scenario "*m3*": *FEI(13)* = "H" and *FEI(28)* = "R";
- Scenario "*m4*": *FEI(13)* = "H" and *FEI(28)* = "H."

4.5 Definition of the optimal assembly cycle and calculation of the optimized collaborative assembly cycle time

To find the scenario with the highest reduction of assembly time, the parameters of Table 3 are calculated and compared. Table 8 explains a summary of the possible MMCs and optimized MMCs of the four identified scenarios and the related

Table 5 Example of a simplified analysis based on the HRAA algorithm applied to task(1): cleaning of internal frame perimeter surface

Collaborative robot	Operator	Task analysis	Best resource (H; R; H or R)
Less ergonomic activities which imply physical and/or mental stress for the operator	Activities which imply reasoning ability, interpretation and responsibility	No recognized ergonomics problem; reasoning, interpretation, and responsibility not required;	H or R
Activities which imply repetitive tasks and/or low task valorization	Activities which imply high handling ability and dexterity	Repetitive task; low-value task; handling ability and dexterity not required;	R
Not Value Adding (NVA) activities	Value Adding (VA) activities	NVA;	R
Activities which require standardization and/or quality improvements	Activities which imply flexibility and ability to adapt	Standard activity; flexibility not required;	R
Does the operator need the help of the robot to perform the task? ("H + R" situation)			NO
FEI(1)			R

Table 6 Industrial case study: FEI(i) values

Task (*i*)	Task name	FEI(i)
1	Cleaning of internal frame perimeter surface	R
2	Internal perimeter adhesive labeling	H
3	Frame cables preparation	H
4	Removing of protective screen film	H
5	Internal perimeter adhesive labeling	H
6	2x Metal bracket assembly (2x small screws and washers for each bracket)	H
7	Positioning of protective screen film	H
8	Removal of perimeter adhesive labels (frame)	H
9	Removal of perimeter adhesive labels (screen cover)	H
10	Insertion of screen cover	R
11	Assembly manual crushing	R
12	Internal cables preparation	H
13	Laying of silicone on the cover group assembly perimeter	H or R
14	Cleaning of perimeter	R
15	Electric parts and support assembly (lower case part)	H
16	Electric parts assembly (cover group part)	H
17	Screen cleaning (paper and compressed air)	R
18	Screen and cover group assembly	R
19	Visual quality check	H
20	Cable insertion and arrangement	H
21	Final insertion and assembly	H
22	Bar-code application, scan, and control	H
23	SW installation, configuration, quality check (real labor time)	H
24	Perimetral screws screwing (20x)	R
25	Perimetral cleaning	R
26	Perimetral adhesive labeling (2x)	H
27	Perimetral rubber cover positioning and fixing	H
28	Cleaning of frontal zone	H or R
29	Plate gluing and positioning (2x)	R
30	UV glue fixing	R
31	Central label positioning	H
32	Final screen cleaning (general and precision) and visual checking	R
33	Final perimetral refinement	H
34	Power supplier preparation	H
35	Final packaging	H

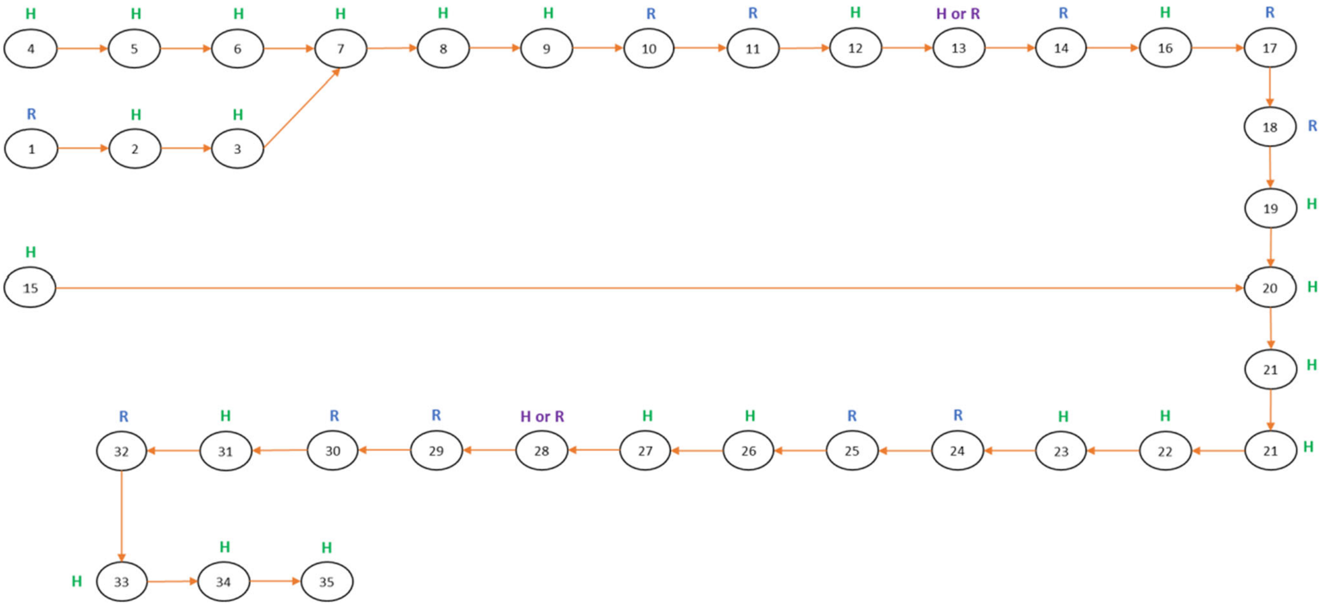


Fig. 3 Assembly priority chart according to the results of Table 6

calculation of parameters needed for the definition of $Tc_{tot}(m)^*$ (see Eq. (7)) and $Tc_{opt}(M)$ (see Eq. (8)).

As presented in all the optimized MMCs, for each scenario, the major improvement comes from the parallelization of activities between the operator and the robot. In particular, the possibility to split task(*15*) in different intervals to be performed during the operator's downtime and in parallel with tasks executed by the robot is crucial.

The final results are exposed in Table 9. From the point of view of cycle time savings, the optimal scenario is "*m1*," which means a full robotic configuration of task(*13*) and task(*28*). The calculated $Tc_{opt}(M)$ is equal to 6.218 (s), The related percentual time reduction with respect to the manual cycle time is 17.16%.

4.6 Final feasibility evaluation

Finally, the economic feasibility evaluation of the identified solutions is provided. In order to calculate the *PBP(M)* according to Eqs. (9) and (10), the data presented in Table 10 are used. Since the required number of end-effectors will be the same for all the scenarios (see also Table 7—common end-effectors can be used for several tasks), the costs for the implementation of the robot cell do not vary. In addition, the operating costs are the same for all the scenarios. Therefore, the final feasibility evaluation will consider only *m1*, because it presents the larger percentual time reduction with respect to the manual cycle time for the same costs ($PBP(M) = PBP(m1) = PBP$). Under different conditions, it

Table 7 Estimation of $t(i)_R$ for tasks with $FEI(i)$ = "R" *or* $FEI(i)$ = "H or R"

Task (*i*)	Description	*FEI(i)*	$t(i)_H$ (s)	$t(i)_R$ (s)
1	Cleaning of internal frame perimeter surface	R	4	8
10	Insertion of screen cover	R	23	46
11	Assembly manual crushing	R	9	18
13	Laying of silicone on the cover group assembly perimeter	H or R	92	184
14	Cleaning of perimeter	R	36	72
17	Screen cleaning (paper and compressed air)	R	32	64
18	Screen and cover group assembly	R	3	6
24	Perimetral screws screwing (20x)	R	260	520
25	Perimetral cleaning	R	40	80
28	Cleaning of frontal zone	H or R	50	100
29	Plate gluing and positioning (2x)	R	44	88
30	UV glue fixing	R	324	649
32	Final screen cleaning (general and precision) and visual checking	R	390	780

Table 8 Summary of the analysis of all possible scenarios

Human-Machine Chart - Scenario "m1" - FEI(13) = R ; FEI (28) = R																																		
task FEI = R	4	5	6	7	2	3	8	9			12			16			19	15	20	21	22	23			26	27				31		33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	0	0	31	0	0	1800	0	0	24	2640	100	30	45	300	0	0	320	300	0	0	0	20	0	50	40	129
task FEI = H	1								10	11		13	14		17	18							24	25			28	29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0	184	72	0	64	6	0	0	0	0	0	0	520	80	0	0	100	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	184	72	1800	64	6	24	2640	100	30	45	300	520	80	320	300	100	88	648	20	780	50	40	129
Optimized Human-Machine Chart - Scenario "m1" - FEI(13) = R ; FEI (28) = R																																		
task FEI = R	4	5	6	7	2	3	8	9	15*	15*	12	15*	15*	16	15*	15*	19	15*	20	21	22	23	15**	15**	26	27	15**	15**	15**	31	15**	33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	46	18	31	184	72	1800	64	6	24	44	100	30	45	300	520	80	320	300	100	88	648	20	780	50	40	129
task FEI = H	1								10	11		13	14		17	18							24	25			28	29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0	184	72	0	64	6	0	0	0	0	0	0	520	80	0	0	100	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	184	72	1800	64	6	24	44	100	30	45	300	520	80	320	300	100	88	648	20	780	50	40	129
Results	*Ta(m)* = 6218 s ; *TH(m)* = 6218 s ; *TR(m)* = 2614 s ; *TH+R(m)* = 0 s ; *Tctot(m)** = 6218 s ; Reduction respect to manual Tc = 17,16%																																	

Human-Machine Chart - Scenario "m2" - FEI(13) = R; FEI (28) = H																																		
task FEI = R	4	5	6	7	2	3	8	9			12			16			19	15	20	21	22	23			26	27	28			31		33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	0	0	31	0	0	1800	0	0	24	2640	100	30	45	300	0	0	320	300	50	0	0	20	0	50	40	129
task FEI = H	1								10	11		13	14		17	18							24	25				29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0	184	72	0	64	6	0	0	0	0	0	0	520	80	0	0	0	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	184	72	1800	64	6	24	2640	100	30	45	300	520	80	320	300	50	88	648	20	780	50	40	129
Human-Machine Chart - Scenario "m2" - FEI(13) = R; FEI (28) = H																																		
task FEI = R	4	5	6	7	2	3	8	9	15*	15*	12	15*	15*	16	15*	15*	19	15*	20	21	22	23	15**	15**	26	27	28	15**	15**	31	15**	33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	46	18	31	184	72	1800	64	6	24	144	100	30	45	300	520	80	320	300	50	88	648	20	780	50	40	129
task FEI = H	1								10	11		13	14		17	18							24	25				29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0	184	72	0	64	6	0	0	0	0	0	0	520	80	0	0	0	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	184	72	1800	64	6	24	144	100	30	45	300	520	80	320	300	50	88	648	20	780	50	40	129
Results	*Ta(m)* = 6268 s ; *TH(m)* = 6268 s ; *TR(m)* = 2514 s ; *TH+R(m)* = 0 s ; *Tctot(m)** = 6268 s ; Reduction respect to manual Tc = 16,49%																																	

Human-Machine Chart - Scenario "m3" - FEI(13) = H ; FEI (28) = R																																		
task FEI = R	4	5	6	7	2	3	8	9			12	13		16			19	15	20	21	22	23			26	27				31		33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	0	0	31	92	0	1800	0	0	24	2640	100	30	45	300	0	0	320	300	0	0	0	20	0	50	40	129
task FEI = H	1								10	11			14		17	18							24	25			28	29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0		72	0	64	6	0	0	0	0	0	0	520	80	0	0	100	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	92	72	1800	64	6	24	2640	100	30	45	300	520	80	320	300	100	88	648	20	780	50	40	129

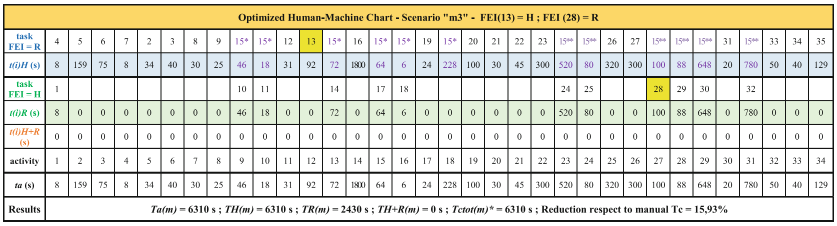
would be necessary to perform a dedicated feasibility evaluation for each of the possible scenarios and considering both the different contributions of the implementation and operating costs.

All the data about the product (manual cycle time, annual production volume, selling price, marginality) and annual production are provided by the company. According to the company's recommendations, the expected product lifecycle is 5 years. The data about the robot implementation and operating cost are estimated according to the research team experience. The calculation of the related *PBP* is provided in Tables 11 and 12. In particular, the former summarizes the *PBP* calculation without considering the ROP contribution. On the other hand, the latter explains the *PBP* calculation including the ROP contribution.

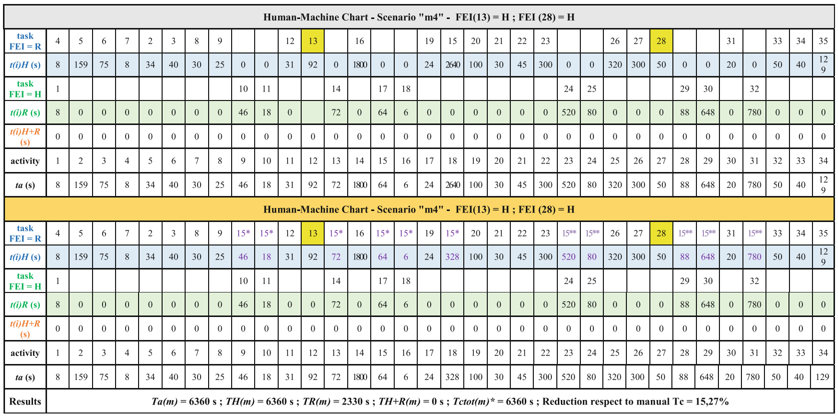
4.7 Analysis of final results

The analyzed case study presents a situation with $N = 2$ (number of tasks which are allocated to "H or R") and a $M = 4$ (scenarios). Results showed that the best possible scenario is m1 (*FEI(13)* = "R" and *FEI(28)* = "R"). The related assembly cycle allows a time reduction with respect to the manual cycle of 17.16 % with a calculated $Tc_{opt}(M)$ equal to 6.218 (s). This information is crucial for the calculation of the *PBP*. In particular, this cycle time reduction entails the possibility to increase the annual productivity by an amount of 86 pieces (+ 17.2%). As the company has the opportunity to expand its market selling more products, the new collaborative workcell can procure a net profit of 23.595 € per year. The related *PBP* (without considering the ROP contribution) is 2.79 years, which means

Table 8 (Continued)



Optimized Human-Machine Chart - Scenario "m3" - FEI(13) = H ; FEI (28) = R																																		
task FEI = R	4	5	6	7	2	3	8	9	15*	15*	12	13	15*	16	15*	15*	19	15*	20	21	22	23	15**	15**	26	27	15**	15**	15**	31	15**	33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	46	18	31	92	72	1800	64	6	24	228	100	30	45	300	520	80	320	300	100	88	648	20	780	50	40	129
task FEI = H	1								10	11			14		17	18							24	25			28	29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0	0	72	0	64	6	0	0	0	0	0	0	520	80	0	0	100	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	92	72	1800	64	6	24	228	100	30	45	300	520	80	320	300	100	88	648	20	780	50	40	129
Results	*Ta(m)* = 6310 s ; *TH(m)* = 6310 s ; *TR(m)* = 2430 s ; *TH+R(m)* = 0 s ; *Tctot(m)** = 6310 s ; Reduction respect to manual Tc = 15,93%																																	



Human-Machine Chart - Scenario "m4" - FEI(13) = H ; FEI (28) = H																																		
task FEI = R	4	5	6	7	2	3	8	9			12	13		16			19	15	20	21	22	23			26	27	28			31		33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	0	0	31	92	0	1800	0	0	24	2640	100	30	45	300	0	0	320	300	50	0	0	20	0	50	40	129
task FEI = H	1								10	11			14		17	18							24	25				29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0		72	0	64	6	0	0	0	0	0	0	520	80	0	0	0	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	92	72	1800	64	6	24	2640	100	30	45	300	520	80	320	300	50	88	648	20	780	50	40	129
Human-Machine Chart - Scenario "m4" - FEI(13) = H ; FEI (28) = H																																		
task FEI = R	4	5	6	7	2	3	8	9	15*	15*	12	13	15*	16	15*	15*	19	15*	20	21	22	23	15**	15**	26	27	28	15**	15**	31	15**	33	34	35
t(i)H (s)	8	159	75	8	34	40	30	25	46	18	31	92	72	1800	64	6	24	328	100	30	45	300	520	80	320	300	50	88	648	20	780	50	40	129
task FEI = H	1								10	11			14		17	18							24	25				29	30		32			
t(i)R (s)	8	0	0	0	0	0	0	0	46	18	0	0	72	0	64	6	0	0	0	0	0	0	520	80	0	0	0	88	648	0	780	0	0	0
t(i)H+R (s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
ta (s)	8	159	75	8	34	40	30	25	46	18	31	92	72	1800	64	6	24	328	100	30	45	300	520	80	320	300	50	88	648	20	780	50	40	129
Results	*Ta(m)* = 6360 s ; *TH(m)* = 6360 s ; *TR(m)* = 2330 s ; *TH+R(m)* = 0 s ; *Tctot(m)** = 6360 s ; Reduction respect to manual Tc = 15,27%																																	

*Represents a task of the current assembly cycle ("Cycle K") which is (partially) executed during operator's downtime in the current assembly cycle ("Cycle K") and in parallel with tasks executed by the robot; **Represents a task of the next assembly cycle ("Cycle K+1") which is (partially) executed during operator's downtime in the current assembly cycle ("Cycle K") and in parallel with tasks executed by the robot; Values written in violet represent the tasks (and related execution time) which are used to optimize the assembly cycle; Values highlighted in yellow represent the tasks which are allocated to "H or R" and which changes according to the specific scenario

a good opportunity for the company to improve productivity and to increase the output of the production workcell.

As often happens, if the use of a collaborative robot is partly justified by the need to improve the operator's OHS conditions, the ROP contribution can also be counted in the feasibility evaluation. In that case, the robot cell purchase and implementation costs as well as the training programs have to be considered in the ROP calculation. Referring to the case study, in this case, the final estimated *PBP* is 1.40 years.

5 Discussion

In this work, an industrial case study related to the manual assembly of a (touch-screen) cash register is presented as an application of the proposed methodology. The results show that the optimal scenario allows a percentual time reduction with respect to the manual cycle of 17.16 % and a *PBP* of 2.79 years (1.40 years considering the ROP contribution). The proposed methodology presents different benefits and simplifications but also some weaknesses, and in particular:

Strengths and advantages:

- The proposed procedure for the scheduling of the optimal assembly cycle is based on the MMC, which is a Gantt-based effective, consolidated and popular tool [34] and as a consequence, it can be easily used in manufacturing companies (especially in SMEs). This should support the diffusion of the collaborative robotics technology also in companies without specific knowledge and expertise in the field.
- The way to find the best solution from the economic point of view is based on the calculation of the *PBP* as the main KPI. This is another common and easy-to-use metric particularly useful to evaluate and compare different industrial investments.
- In addition, the possibility to (eventually) add the ROP contribution in the feasibility analysis will further support companies in justifying the required investments.

Table 9 Summary of the final results

Scenario	Allocation task(*13*) – task(*28*)	*Tctot(m)** (s)	Reduction respect to actual cycle time (%)
m1	R-R	6218	17,16
m2	R-H	6268	16,49
m3	H-R	6310	15,93
m4	H-H	6360	15,27

Table 10 Data needed for PBP calculation

GENERAL DATA	
Expected plant lifecycle (years)	5
Work shift period (h/day)	8
Annual workdays (day/year)	220
Annual robot programming and set-up time (h/year)	352
Average robot utilization (h/year)	2.112
NET PROFITS ANALYSIS	
Potential extra-production	
Cycle time reduction with respect to the actual one (%)	17,16
Annual production volume (pcs/year)	500
Product selling price (€/pc)	1.100,00
Product marginality with respect to selling price (%)	25
Annual saved operator time (h/year)	148
Annual extra-production (pcs/year)	86
Annual net extra profits (€/year)	23.595,00
Return on prevention	
Total return on prevention (€)	116.600,00
Annual return on prevention (€/year) (spread over the plant lifecycle)	23.320,00
COSTS ANALYSIS	
Implementation cost	
Collaborative workcell purchase and implementation cost (€)	50.000,00
Operator’s training cost (€)	3.000,00
Operating cost	
Annual robot cell maintenance cost (€/year) (5% of investment cost)	2.500,00
Average robot cell electric consumption (W/h)	200,00
Average energy cost (€/KWh)	0,12
Annual robot cell energy consumption cost (€/year)	50,69

Weaknesses and limits:

- The presented methodology is strictly related to the allocation of the tasks between the human and the robot. To this end, the methodology developed in [29, 30] is suggested. Nevertheless, it is possible to use other approaches. It is important that the used methodology for task allocation carefully considers the advantages and disadvantages of both the human and the robot during the assembly task. An error in this evaluation could compromise the effectiveness of the calculation of the optimal collaborative assembly cycle.
- Another important weakness is the accuracy with which assembly times are estimated, which mainly depends on the approach used for this evaluation (simulation-based and coefficient-based).
- Finally, the use of the PBP as the main KPI for the feasibility evaluation has many advantages but also limitations. In fact, a more complete economic analysis should include further metrics to better evaluate the effectiveness of the investments.

Table 11 PBP calculation without considering the ROP contribution

Profits	Annual net extra profits (€/year)	23.595,00
	Total (€/year)	23.595,00
Investments	Robot cell purchase and implementation cost (€)	50.000,00
	Operator's training cost (€)	3.000,00
	Total robot cell maintenance cost over lifecycle (€)	12.500,00
	Total robot cell energy consumption cost over lifecycle (€)	1.267,00
	Total (€)	66.767,00
Payback period (year)		2,79

6 Conclusions and outlook

This work presents a six-step methodology for the systematic design of an optimized collaborative assembly and related cycle. In particular, the proposed research questions have been addressed by providing:

- A systematical methodology for the design of human-centered and collaborative assembly systems starting from manual assembly workstation (see RQ1);
- An optimal scheduling of the assembly cycle by considering the product and process main features as well as tasks allocation (see RQ2);
- A way to find the best solution from the economic point of view based on the calculation of the PBP as the main KPI (see RQ3);
- An approach based on tools with which manufacturing companies are familiar and that are easy to use (a general requirement for application in SMEs);

Nevertheless, future improvements and development are needed to further improve the methodology. These are presented in the following:

1. Development of more accurate coefficients for the estimation of the robot task execution time $t(i)_R$

This methodology proposes two options for the determination of the robot task execution time $t(i)_R$. In particular, the approach based on the use of coefficients (C_1, C_2) could be improved by providing more reliable values. Of course, the speed of a collaborative robot (and therefore the related robot execution time) strictly depends on the possibility to implement different collaborative operations [4]. As a consequence, the development and experimental investigation of

Table 12 PBP calculation considering the ROP contribution

Profits	Annual net extra profits (€/year)	23.595,00
	Annual Return on Prevention (€/year)	23.320,00
	Total (€/year)	46.915,00
Investments	Robot cell purchase and implementation cost (€)	50.000,00
	Operator's training cost (€)	3.000,00
	Total robot cell maintenance cost over lifecycle (€)	12.500,00
	Total robot cell energy consumption cost over lifecycle (€)	1.267,00
	Total (€)	66.767,00
Payback period (year)		1,40

coefficients which are more accurate, application-specific, and oriented on the different possible collaborative operations will provide important benefits to the methodology both in terms of estimation reliability and velocity.

2. Development of other methodologies for the definition of the optimal assembly cycle

The possibility to use other methodologies should be investigated. A possibility could be to use a multi-method approach able to identify with different techniques the best result among all the others. In this context, the use of artificial intelligence techniques based on operational research could be an interesting opportunity.

Furthermore, the proposed methodology is based on the concept of static allocation of tasks between the human and the robot. For sure, the dynamic task allocation will be crucial in future collaborative assembly systems. The possibility to choose in real time and indiscriminately which task will be the next one according to the operator's needs and wants could significantly improve cognitive ergonomics conditions, operator's well-being, and production flexibility [30]. In addition, the possibility to dynamically change task assignment to adapt to production changes and to prevent outages will be crucial for future collaborative assembly systems, especially for SMEs [38]. Nevertheless, this possibility is not always implementable. In fact, a dynamic allocation of activities will be possible only for such tasks that do not present limiting features. In fact, in a collaborative process, there might be tasks that are uniquely suitable for humans and others uniquely suitable for robots due to the following limitations:

- Technical limitations—a task which presents technical constraints (i.e., performing activities characterized by high dexterity or necessity of reasoning ability) cannot be performed by a robot competitively [29, 39]. For this reason, such task will not be executable in a dynamic way since its allocation must be strictly defined in advance (only humans can perform it);
- OHS limitations—a task which implies unsafe/unhealthy work conditions (i.e., performing hazardous activities) or physical/cognitive overload (i.e., the handling of heavy objects under unfavorable conditions) should be performed by the robot [15, 40]. Also, in this case, the task allocation cannot be variable;
- Economic limitations—the use of collaborative robots for the partial and flexible automation of manufacturing processes presents particular economic advantages over manual labor for a medium range of lot sizes [41]. In this case, a dynamic allocation will be possible even if it would entail a negative effect from the economic and productive point of view.

As a consequence, to implement a dynamic task allocation, it will be necessary to carefully consider the abovementioned limitations. In addition, the continuous change in task execution has to dynamically be evaluated in the search of the optimal assembly sequence.

3. Enlargement of the methodology by adding a further step (7th) related to the final implementation of the collaborative assembly workstation

The proposed methodology ends with the definition of the optimal assembly cycle according to the task allocation. In the future, the final result of the design process could also include "how" to physically implement the collaborative solution on the shop floor. For this reason, a final step which includes a set of workstation design requirements and related guidelines could be added to the framework. The authors are currently working on a catalog of design guidelines for human-robot collaborative assembly. Basically, the main and general requirements to be satisfied in the design of the workstation are [42]:

a. Minimize the occupational risks (especially the mechanical one) for health and safety which can occur during the interaction between the operator and the robotic systems and/or between the operator and the other elements of the workstation;
b. Maximize the operator wellbeing during the interaction with the robot and with other elements of the workstation in terms of physical and cognitive ergonomics;
c. Minimize the tasks time and costs for manual, robotic, and collaborative tasks, especially for assembly.

This has to be added combined with specific product design requirements for products planned for human-robot collaborative assembly in order to develop a general and complete list of guidelines for the proper development of future industrial collaborative applications by considering product and process integration [43].

4. Adding further economic KPIs used for the detailed investment evaluation

To become more complete, the feasibility analysis should be supported by additional economic KPIs capable to better quantify the global effectiveness of the investments. As just an example, a possibility could be the so-called net present value (NPV), which basically is able to quantify the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

Finally, future works should focus on the development of specific software to properly implement the proposed methodology. This should be integrated with other works presented by the authors about the design of collaborative assembly systems. The software will allow a general simplification and automation of the design process by facilitating its adoption and use by companies.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Luca Gualtieri under the supervision of Dr. Erwin Rauch. The first draft of the manuscript was written by Luca Gualtieri and Erwin Rauch and all authors commented on previous versions of the manuscript. Prof. Renato Vidoni reviewed and edited the internal draft of the work. All authors read and approved the final manuscript.

Funding Open access funding provided by Libera Università di Bolzano within the CRUI-CARE Agreement. This work was supported by the Open Access Publishing Fund of the Free University of Bozen-Bolzano.

Compliance with ethical standards

Data availability Not applicable

Ethical approval and consent to participate The research activity envisaged in this work has been conducted applying fundamental ethical principles and relevant national, EU, and international legislation. We confirm that all the authors involved in the writing of this article are aware of this work and approve all its contents.

Consent for publication We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. The authors further confirm that the order of authors listed in the manuscript has been approved by all of us.

Competing interests The authors declare no competing interests.

References

1. Kagermann H, Helbig J, Hellinger A, Wahlster W (2013) Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group. Forschungsunion
2. Boston Consulting Group (2015) Boston Consulting Group. Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. https://www.bcg.com/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries.aspx, visited on June 2020.
3. International Federation of Robotics (2019) IFR Publishes Collaborative Industrial Robot Definition and Estimates Supply. 2019. https://ifr.org/post/international-federation-of-robotics-publishes-collaborative-industrial-rob. Accessed on March 2020.
4. International Organization for Standardization (2016) ISO TS 15066—Robots and Robotic Devices—Collaborative Robots (ISO/TS 15066:2016). https://www.iso.org/standard/62996.html.
5. Rauch E, Unterhofer M, Rojas RA, Gualtieri L, Woschank M, Matt DT (2020) A maturity level-based assessment tool to enhance the implementation of Industry 4.0 in small and medium-sized enterprises. Sustainability 12(9):3559
6. Orzes G, Rauch E, Bednar S, Poklemba R (2018) Industry 4.0 implementation barriers in small and medium sized enterprises: a focus group study. In: 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). IEEE, pp 1348–1352
7. Çil ZA, Li Z, Mete S, Özceylan E (2020) Mathematical model and bee algorithms for mixed-model assembly line balancing problem with physical human–robot collaboration. Applied Soft Computing:106394
8. Weckenborg C, Kieckhäfer K, Müller C, Grunewald M, Spengler TS (2019) Balancing of assembly lines with collaborative robots. Business Research:1–40
9. Xu W, Tang Q, Liu J, Liu Z, Zhou Z, Pham DT (2020) Disassembly sequence planning using discrete Bees algorithm for human-robot collaboration in remanufacturing. Robotics and Computer-Integrated Manufacturing 62:101860
10. Cheng Y, Sun L, Liu C, Tomizuka M (2020) Towards efficient human-robot collaboration with robust plan recognition and trajectory prediction. IEEE Robotics and Automation Letters 5(2):2602–2609
11. Mateus JC, Claeys D, Limère V, Cottyn J, Aghezzaf EH (2020) Base part centered assembly task precedence generation. The International Journal of Advanced Manufacturing Technology 107(1):607–616
12. Zhang J, Liu H, Chang Q, Wang L, Gao RX (2020) Recurrent neural network for motion trajectory prediction in human-robot collaborative assembly. CIRP Annals.
13. Fager P, Calzavara M, Sgarbossa F (2020) Modelling time efficiency of cobot-supported kit preparation. The International

Journal of Advanced Manufacturing Technology 106(5):2227–2241

14. Mateus JC, Claeys D, Limère V, Cottyn J, Aghezzaf EH (2019) A structured methodology for the design of a human-robot collaborative assembly workplace. The International Journal of Advanced Manufacturing Technology 102(5-8):2663–2681
15. Malik AA, & Bilberg A (2019) Complexity-based task allocation in human-robot collaborative assembly. Industrial Robot: the international Journal of Robotics Research and Application 46(4):471–480. https://doi.org/10.1108/IR-11-2018-0231
16. Herfs W, Storms S, Petrovic O (2019) An approach on simplifying the commissioning of collaborative assembly workstations based on product-lifecycle-management and intuitive robot programming. In: International Conference on Intelligent Human Systems Integration. Springer, Cham, pp 43–49
17. Rahman SM, Wang Y (2018) Mutual trust-based subtask allocation for human–robot collaboration in flexible lightweight assembly in manufacturing. Mechatronics 54:94–109
18. Jungbluth J, Gerke W, Plapper P (2017) An intelligent agent-controlled and robot-based disassembly assistant. In IOP Conference Series: Materials Science and Engineering (Vol. 235, No. 1, p. 012005). IOP Publishing.
19. Gabler V, Stahl T, Huber G, Oguz O, Wollherr D (2017) A game-theoretic approach for adaptive action selection in close proximity human-robot-collaboration. In 2017 IEEE International Conference on Robotics and Automation (ICRA) (pp. 2897-2903). IEEE
20. Faber M, Mertens A, Schlick CM (2017) Cognition-enhanced assembly sequence planning for ergonomic and productive human–robot collaboration in self-optimizing assembly cells. Production Engineering 11(2):145–154
21. Faber M, Kuz S, Mertens A, Schlick CM (2016) Model-based evaluation of cooperative assembly processes in human-robot collaboration. In: Advances in Ergonomics of Manufacturing: Managing the Enterprise of the Future. Springer, Cham, pp 101–112
22. Gualtieri L, Palomba I, Merati FA, Rauch E, Vidoni R (2020) Design of human-centered collaborative assembly workstations for the improvement of operators' physical ergonomics and production efficiency: a case study. Sustainability 12:3606
23. Malik AA, Masood T, Bilberg A (2020) Virtual reality in manufacturing: immersive and collaborative artificial-reality in design of human-robot workspace. International Journal of Computer Integrated Manufacturing 33(1):22–37
24. Tang KH, Ho CF, Mehlich J, Chen ST (2020) Assessment of handover prediction models in estimation of cycle times for manual assembly tasks in a human–robot collaborative environment. Applied Sciences 10(2):556
25. Hanna A, Bengtsson K, Dahl M, Erős E, Götvall PL, Ekström M (2019) Industrial challenges when planning and preparing collaborative and intelligent automation systems for final assembly stations. In: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA). IEEE, pp 400–406
26. Lemmerz K, Glogowski P, Hypki A, Kuhlenkoetter B (2018) Functional integration of a robotics software framework into a human simulation system. In: ISR 2018; 50th International Symposium on Robotics. VDE, pp 1–8
27. Malik AA, Bilberg A (2018) Digital twins of human robot collaboration in a production setting. Procedia manufacturing 17: 278–285
28. Malik AA, Bilberg A (2017) Framework to implement collaborative robots in manual assembly: a lean automation approach. In: Katalinic B (ed) Proceedings of the 28th DAAAM International Symposium. Published by DAAAM International, ISSN, pp 1726–9679
29. Gualtieri L, Rauch E, Vidoni R, Matt DT (2019) An evaluation methodology for the conversion of manual assembly systems into human-robot collaborative workcells. Procedia Manufacturing 38: 358–366
30. Gualtieri L, Rojas RA, Ruiz Garcia MA, Rauch E, Vidoni R (2019) Implementation of a laboratory case study for intuitive collaboration between man and machine in SME assembly. In: Matt DT, Modrak V, Zsifkovits H (eds) In Industry 4.0 for SMEs Challenges, Opportunities and Requirements. Palgrave Macmillan, Basingstoke, UK
31. Antonelli D, Bruno G (2017) Dynamic task sharing strategy for adaptive human-robot collaborative workcell. DEStech Transactions on Engineering and Technology Research, (icpr).
32. Tecnomatix (2020) https://www.plm.automation.siemens.com/global/en/products/tecnomatix/. Accessed on March 2020.
33. Hitomi K (2017) Manufacturing systems engineering: a unified approach to manufacturing technology, production management and industrial economics. Routledge
34. Wilson JM (2003) Gantt charts: a centenary appreciation. European Journal of Operational Research 149(2):430–437
35. Rathod AS, Jadhav RG, Babar AB (2016) An overview of method study and study of different recording techniques. International Journal of Science and Research 5(8):1484–1491
36. Gualtieri L, Palomba I, Wehrle E, Vidoni R (2019) The opportunities and challenges of SME manufacturing automation: safety and ergonomics in human–robot collaboration. In: Matt DT, Modrak V, Zsifkovits H (eds) Industry 4.0 for SMEs Challenges, Opportunities and Requirements. Palgrave Macmillan, Basingstoke, UK
37. Council BS (2014) The business benefits of health and safety: a literature review. UK, London
38. Antonelli D, Bruno G (2019) Dynamic distribution of assembly tasks in a collaborative workcell of humans and robots. FME Transactions 47(4):723–730
39. Ranz F, Hummel V, Sihn W (2017) Capability-based task allocation in human-robot collaboration. Procedia Manufacturing 9:182–189
40. Siciliano B, Khatib O (2016) Springer Handbook of Robotics. Springer, Berlin and Heidelberg. https://doi.org/10.1007/978-3-540-30301-5
41. Fryman J, Matthias B (2012, May) Safety of industrial robots: From conventional to collaborative applications. In: ROBOTIK 2012; 7th German Conference on Robotics. VDE, pp 1–5
42. Gualtieri L, Rauch E, Vidoni R, Matt DT (2020) Safety, ergonomics and efficiency in human-robot collaborative assembly: design guidelines and requirements. In: 2020 CIRP Design Conference, 5-8 May 2020, Online Conference
43. Gualtieri L, Pasetti Monizza G, Rauch E, Vidoni R, Matt DT (2020) From design for assembly to design for collaborative assembly - product design principles for enhancing safe and ergonomic human-robot collaboration. In: 2020 CIRP Design Conference, 5-8 May 2020, Online Conference