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 © The Author(s) 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...
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 ques-
tions. Section 3 deals with the development of the meth-
odology for the design of human-centered and collabora-
tive assembly systems starting from manual assembly
workstation, particularly focusing on the definition of the
optimal collaborative assembly cycle and to the pre-
liminary feasibility evaluation. Section 4 presents the
application of the abovementioned approach by means of an
industrial case study. Finally, the discussions and conclu-
sions 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 fo-
cusing on the definition of a collaborative assembly cycle is
provided.

The following works related to different methodolo-
gies for the planning of HRI tasks and for the develop-
ment 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 pur-
poses by implementing an optimized disassembly se-
quence. 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 assem-
bly. 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] pro-
vided a methodology for information extraction and pro-
cessing 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 commission-
ing of HRC processes by combining product-lifecycle-
management with collaboration-specific process plan-
ing. Rahman and Wang [17] presented a two-level
feedforward optimization strategy that determines opti-
imum subtask allocation before the assembly starts.
Jungbluth et al. [18] presented software based on prod-
uct model used to propose a disassembly plan by de-
veloping 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 opti-
mal assembly sequence planner by using a complete
assembly graph of the final product as well as the er-
gonomic 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 col-
laborative assembly when different handover prediction
models were applied. Hanna et al. [25] analyzed the chal-
 lenges with current planning and preparation processes for
the final collaborative assembly. Lemmerz et al. [26] de-
veloped an overall simulation tool for the design of col-
laborative assembly systems. Malik and Bilberg [27] pro-
posed a digital twin framework to support the design,
build, and control of human-machine cooperation for as-
sembly works. Malik and Bilberg [28] presented a sys-
tematic 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 method-
ology for the design of collaborative assembly worksta-
ions starting from manual ones, which also considers the
different possibilities in terms of human-robot task allo-
cation, has not been extensively investigated. In particu-
lar, an intuitive and simple methodology for a static as-
sembly 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].
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 C1 and C2 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 C1. 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 C2. 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

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**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 |

**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”;          | t(i)H = C1* t(i)H                                         | C1 = 2            |
| FEI(i) = “H or R”      | t(i)H-R = C2* t(i)H                                        | C2 = 0.7          |
| FEI(i) = “H + R”       |                                                           |                   |
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 \([FEI(i) = \text{"H or R"})\), 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 \((T_{copt}(m)^*)\) is provided in Eq. (7). The computation of the best assembly cycle time among all scenarios \((T_{copt}(M))\) is provided in Eq. (8). The parameters and the equations needed for the calculation of \(T_{copt}(m)^*\) and \(T_{copt}(M)\) 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])](image)
Table 3 Parameters and equations for the calculation of $T_{c_{opt}}(m)^*$ and $T_{c_{opt}}(M)$ referring to the optimized MMC

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

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;
- $t(i)_H$ 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($i(i)$ 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+l”). 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 $T_{c_{opt}}(m)^*$ (for a certain scenario $m \in M$) and $T_{c_{opt}}(M)$:

$$T_{c_{opt}}(m)^* = T_a(m) + T_{H+R}(m) \quad [s/pcs] \quad (7)$$

$$T_{c_{opt}}(M) = \min \left\{ T_{c_{opt}}(m)^* \right\} \forall m \in M \quad [s/pcs] \quad (8)$$

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 in the methodology. The best solution among the various scenarios \( (PBP(M)) \) will be the one with the lowest PBP value (see Eq. (10)).

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

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

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 in 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 \(FEI(i) = \text{“H”}\), 11 tasks with \(FEI(i) = \text{“R”}\), and two tasks with \(FEI(i) = \text{“H or R”}\). 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 the analyzed case study. Table 7 provides the estimation of \(t(i)_{R}\) for the analyzed case study.
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 $FEI(28) = “H”$;
- 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 | 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      |
calculation of parameters needed for the definition of $T_{ctot}(m)^*$ (see Eq. (7)) and $T_{copt}(M)$ (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 $T_{copt}(M)$ 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

| Task (i) | Description                                      | $FE(i)$ | $t(i)_{H}$ (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            |
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 $M = 4$ (scenarios). Results showed that the best possible scenario is $m_1$ ($FEI(13) = "R"$ and $FEI(28) = "R"$). The related assembly cycle allows a time reduction with respect to the manual cycle of 17.16% with a calculated $T_{copt}(M)$ 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
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                                       |
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.

### 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
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.

| Table 12 PBP calculation considering the ROP contribution |
|-----------------------------|-----------------|-----------------|
| **Profits** | **Investments** |
| Annual net extra profits (€/year) | Robot cell purchase and implementation cost (€) |
| 23,595,00 | 50,000,00 |
| Annual Return on Prevention (€/year) | Operator's training cost (€) |
| 23,320,00 | 3,000,00 |
| Total (€/year) | Total robot cell maintenance cost over lifecycle (€) |
| 46,915,00 | 12,500,00 |
| **Total (€)** | Total robot cell energy consumption cost over lifecycle (€) |
| 66,767,00 | 1,267,00 |

**Payback period (year)**

1,40
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.

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