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Method for the evaluation of layout options for a human-robot collaboration

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Abstract

During times of flexible production, the human-robot collaboration has the potential for flexible automation within the assembly process. Optimization of manual assembly workstations focuses on the workspace layout in particular. The storage boxes are placed within the grasping area of the human in order to save time. Regarding an application in a human-robot collaboration, there are several criteria for finding the appropriate layout for an assembly task. This paper describes identified criteria regarding the layout which have an influence on an efficient collaboration. These criteria include amongst others the movement lengths of human and the robot, the freedom of movement of the human depending on the robot's position, and the flexibility of the robot to perform a certain action. These criteria are used for an evaluation method in order to find the most fitting layout for the assembly task being considered. For the evaluation, the user provides inputs such as the percentages of various defined operating modes or defines the criteria, which should be taken into account.

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Keywords: flexible manufacturing system, hybrid assembly system, robot

1. Introduction

The trend towards more individualized products results in a higher number of variants [1]. In addition, product life cycles are decreasing, thus requiring a production process that can adapt quickly to changes [2]. The combination of these two facts results in a demand for a flexible production process. The human being is still the most flexible resource and can easily adapt to changes. However, due to high wages, the achievement of production in high-wage countries requires strategies for reducing the work force, for example by automation.

The collaboration between human and robot is an approach for closing the gap between manual assembly and automation. The main assembly task is divided into subtasks, which are allocated to the human and robot resources. Thus, both resources can execute tasks according to their strengths [3]. The robot's tasks are the ones easier to automate, and the human's tasks are the ones that require cognitive skills. This is advantageous because tasks that are easy to automate can also be programmed quickly [4].

Regarding manual assembly processes, the planning methods consider as one aspect as being the layout of the assembly workspace. Within this process, the paths for grasping the parts are optimized by reducing the lengths thereof and allocating the storage boxes according to their importance [5].

Therefore, the two resources within the workspace, i.e. the human and the robot, need to be placed according to their required movement areas. In order to work together, the robot needs to move in close proximity to but not disturb the human. Thiemermann found out that with increasing distance between robot and human, the robot speed can be higher [4]. The robot could be placed far away from the human, but this would lead to a less efficient collaboration due to longer grasping lengths.

The implication is that several criteria exist which influence the layout with respect to time and ergonomics. In this approach, a method is introduced in which various layouts in a human-robot-collaboration are compared using several identified criteria. After applying the method, the user receives a layout recommendation for the application.

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Following an introduction of the state of the art in the next section, the method for the evaluation of the layouts indcluding the identified criteria will be described. This is then followed by an evaluation of the method and a summary.

2. The state of the art

The topic of the approach concerns the planning of human-robot collaboration, layout planning in particular along with the simulation of these applications since a variety of layouts can be regarded in a simulation. Therefore, approaches in the field of planning an application are first introduced before describing approaches for a simulation. The layout evaluation is embedded in a task-oriented programming approach for human-robot collaboration that the final section within this chapter describes.

2.1. Application Planning with respect to layout in a human-robot collaboration

The approach in Beumelburg is a capability-based planning method for human-robot collaborative applications. The author first defines criteria which relate to the assembly process, ergonomics, the assembly parts, and their delivery. There are several parameter values for each of these criteria. The assembly task is divided into assembly operations, and different criteria with parameter values are allocated to each operation. The criteria are evaluated based on better/worse decisions and transferred afterwards to an ordinal scale where 0 is the worst and 1 the best. In evaluating the criteria, the capability for both resources is described, thus forming the basis for the task allocation. [6, 7].

Thiemermann (2005) presents layout concepts for human-robot collaboration applications. He describes requirements for the layout of the collaborative workspace and gives three concepts as layout options. In each concept, the robot is located opposite the human, and there is either one common workspace, two common workspaces or one common workspace as well as one workspace for the human. Furthermore, Thiemermann gives possible options for the supply of material. [4].

Tsarouchi et al. (2016) evaluate different layouts based on criteria. The latter include the area of the workspace, the accessibility of passive resources, the ergonomics, and the investment made. The tasks of both resources and their capabilities are taken into account for the evaluation. A visualization displays the recommended layout afterwards [8].

Faber et al. describe requirements for the design of a collaborative workplace. In doing so, they evaluate human requirements, technical requirements, and current legal regulations. Some examples for requirements are that the dimensions of the workspace should match the dynamic forces of the robot and its possible payload or that the height of the assembly table should be adjustable, e.g. positions for material. The requirements are described for the various phases of the product life cycle: manufacturing, distribution, utilization, and reuse [9].

Thomas introduces a method for evaluating potential applications in an early planning phase. The software for the evaluation contains 60 criteria concerning the areas of personnel, parts, assembly task, technical constraints, and the production system. The result of the evaluation is a recommendation of whether the application is feasible for a manual workplace, an automated workplace, or human-robot collaboration [10].

Although some of the approaches describe concepts for layouts or requirements, a comparison of different layout options regarding a specific example of use has not been described. A simulation can be suitable for the planning or comparison of layouts. Therefore, the next section describes approaches for the simulation of human-robot collaborative workspaces.

2.2. Simulation for layout evaluation in human-robot collaboration

Regarding simulation of manual assembly and humans, digital human models can be used in order to evaluate the accessibility of parts or to optimize the cycle time [11]. Common digital human models are Jack, Ramsis [11] and Human Builder [13]. However, the integration of robots with these models is not possible. Therefore, there are few approaches regarding the simulation of human-robot collaboration workspaces [12].

Ore et al. (2016) describe an approach for evaluating an application through simulation. The simulation model contains both the human and the robot resources. The output of the simulation is the cycle time and the biomechanical stress. The times for the human motions are calculated based on MTM. Data and the description of the environment are the basis for calculating the robot's times. The Rapid Upper Limb Assessment (RULA) model is applied for the evaluation of biomechanical stress [14].

Lemmerz et al. (2018) simulate a human-robot collaboration scenario using Editor for Manual Work Activities (EMA) and Robot Operating System (ROS). The simulation model for the human is represented within EMA, whereas the robot model is set up in ROS. Within EMA, the cycle times and ergonomics of the human are evaluated and subsequently sent to ROS, while the robot's paths are taken into account and the combination of both resources is evaluated [12, 15].

This section shows that there are not yet many possibilities for the simulation layouts for a human-robot collaboration. Therefore, there is a need for a method regarding the evaluation of different layouts.

2.3. Task.oriented programming system

A system for user-centered programming of a robot in a human-robot-collaboration is introduced by Berg et al. (2017). This system contains a planning module that supports the user allocating the tasks to the human and the robot. A recommendation for the allocation is presented to the user and displayed on the user interface [16].

The planning module develops this recommendation in three steps. Firstly, the assembly plan is derived from the Computer-aided design (CAD) product. The tasks along with their member parts are described within this assembly plan. A capability test evaluates which resource, human or robot, is capable of executing the tasks. Afterwards, the scenario planner allocates the tasks to the human and the robot. After the first allocation of tasks to the resources, the herein described layout evaluation takes place. The programming system is capable of assembly operations for smaller products on an assembly table. The robot is located on a side table and should not be located on a wall. The approach for the evaluation of the layout was applied with a Universal Robot. The human model is fixed by the simulation tool and therefore doesn't represent any percentiles.

3. Method for the comparison of the work place layout for human-robot collaboration

Based on the constraints described at the end of the last chapter, this section describes the method developed of taking the layout of the workplace into account.

3.1. Different layout options

The aim of this method is to provide a suitable workplace layout for human-robot collaboration depending on the assembly task. Therefore, different concepts of layouts were developed. They vary in the four main degrees of freedom (see Fig. 1), which are the position of the robot's base, the human's position, the type of material supply and the number as well as the position of the small carriers. The height of the robot's base is adjusted to that of the assembly table because lowering it leads to a higher collision potential with the assembly table and increasing it reduces the reachability of parts on the assembly table. Furthermore, the robot's material is separated from that of the worker and is set to six small carriers per resource. To ensure low physical load for the employee, their material is either provided by slides (see Fig. 2 (a-c)) or in consideration of the worker's handling area (see Fig. 2 (d-g)). Two layouts suggested by [4] (see Fig. 2 (h-i)) are also considered. The concepts shown can also be applied to those where the worker stands on the right and the robot on the left side of the assembly table. The resources and material supply can be varied as

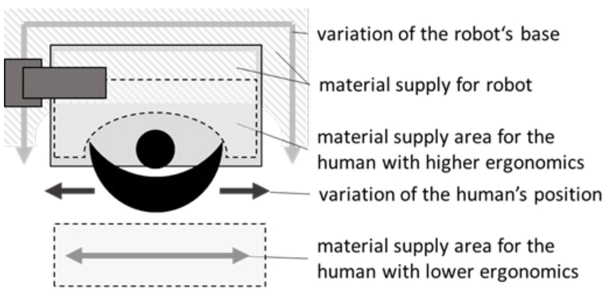


Fig. 2: Variations of the resource positions and material supply areas

shown in the following Fig.1.

Varying the four degrees of freedom (Fig. 2) leads to possible layouts shown in (Fig. 1).

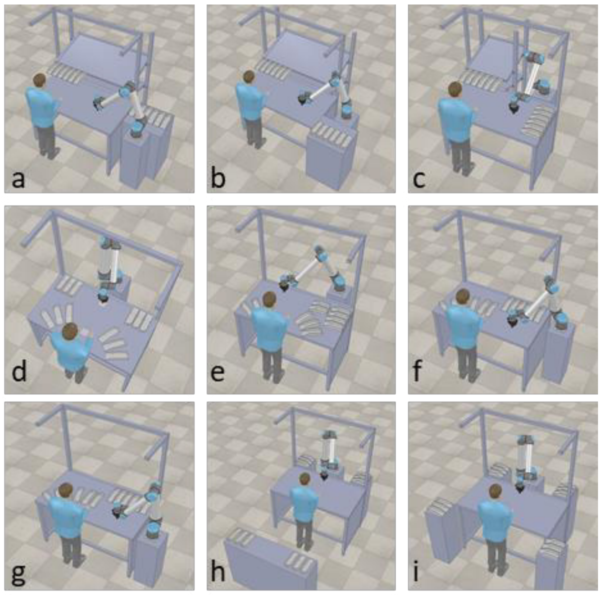


Fig. 1: Different layout options according to the degrees of freedom

3.2. Method for the comparison of layouts

This method is based on a list of 30 criteria that depend on the current state of teamwork. Therefore, there exist different categories (cmp. Table 1). First, a distinction is made between the following four operating modes: manual mode, automation, parallelization, and collaboration. The latter takes place when both resources work together at a small distance from the same product, whereas parallelization forbids direct contact and is especially suitable for pre-assembly. Second, the method differentiates between the task execution by either human or robot. As most of the criteria can be either assigned to material handling or assembling, this distinction takes place third so that a maximum space of 4*2*2=16 categories would ultimately result. As some combinations, e.g. manual mode and the robot as a resource, are mutually exclusive, and the criteria for the operating mode collaboration are viewed in a collective manner, the result is the nine categories cg_1-cg_9 shown in Table 1. The criteria for each category are given different weighting factors based on user input and are later used to compare the various layouts.

Table 1: Categorization of the criteria

Category	Operating mode	Work Pattern	Resource
cg_1	Manual	Handling	Human
cg_2	Manual	Assembling	Human
cg_1	Automation	Handling	Robot
cg_4	Automation	Assembling	Robot
cg_5	Parallelization	Handling	Human
cg_6	Parallelization	Assembling	Human
cg_7	Parallelization	Handling	Robot
cg_8	Parallelization	Assembling	Robot
cg_9	Collaboration	Collaboration	both

The software tool developed requests the following four user inputs: First, the time percentages of the four operating modes have to be inserted based on an existing task allocation between human and robot (N_1). Second, an estimation of the allocation between the material handling and assembling for both resources is requested (N_2). Third, a list of all criteria is provided, and the user selects those which he considers highly important (N_3) and mediocre important (N_4).

Three types of so-called centers of assembly are defined to ensure the comparison of the nine layouts. These respectively reflect the position where the human and/or the robot are working at as a function of the operating mode. First, the human center of assembly (hca) is always placed in front of the employee in view of ergonomics. Second, for automation and parallelization, the robot center of assembly (rca) is defined at the center of its intended area. Finally, determining the collaborative center of assembly (cca) reveals conflicting aims. On the one hand, the cca should be as close as possible to the hca due to ergonomics. On the other hand, placing it near the rca may reduce the assembly time because the robot may only move very slowly under the current standards. The cca was defined at the border between both the areas of the human and the robot. The distance from the leading edge was kept constant so that the co-worker does not have to bend forward. The concepts in which the robot is placed next to the employee show three different positions for the centers of assembly, whereas those where both resources are facing each other have a combined hca and cca (Fig 3).

a b

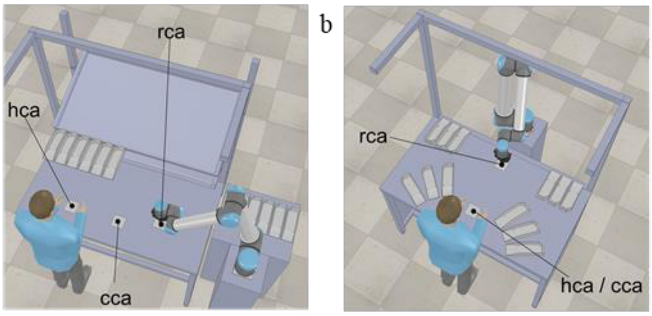


Fig 3: (a) distinguished centers of assembly, (b) combined centers of assembly

The approach for evaluating each of the nine concepts taking the user inputs into account is described hereinafter and shown in Fig. 4. It uses the aforementioned approach from Beumelburg (2005), which maps the main business goals of time, quality, and cost to the assembly in terms of cycle time, ergonomics, process reliability, and additional investment [7]. Since the latter depends on specific assembly operations, it was not considered. Also, cycle time and ergonomics are often interdependent and are thus viewed in a collective manner.

First, the chosen criteria with high (N_3) and mediocre importance (N_4) are each split into those of additional investment ($c_{xi,ai}$) and cycle time and ergonomics ($c_{xi,ce}$). These are then linked in the calculation with the evaluation matrix M_e and the categorization matrix M_c. M_e contains the assessment of the nine layouts with regard to the 30 criteria. Therefore, it is a $n \times 9$ matrice. M_c. includes the assignment of each criterion to the nine categories cg_1-cg_9. One criterion may have relevance with regard to several categories. Evaluating 30 criteria and 9 categories, it is a 30×9 matrice and contains binary values. Within the first step, which is the evaluation of the cost criteria, the assessment for the criteria are taken out of the matrice M_e. For the other criteria regarding the ergonomics and cycle time, the assessment is taken out of matrice M_e and the criteria is evaluated towards the 9 categories using matrice M_c. This is because the criteria concerning cycle time and ergonomics are weighted based on the allocation of the tasks. The allocation of the tasks however doesn't influence the additional costs. The result of this steps are four kinds of matrices. $M_{hi,ai}$ and $M_{mi,ai}$ contain the evaluation of the layouts regarding the chosen criteria. For $M_{hi,te}$ and $M_{mi,te}$, there exist respectively nine matrices. For each category one matrice exists and contains the evaluation of the chosen criteria.

In the following, the mean value is calculated over the columns of each matrix, which ensures an equal weighting of the criteria within each category. The result on the one hand is the vectors $v_{hi,ai}$ and $v_{mi,ai}$, which contain the average evaluation of the selected criteria of the additional investment. The result on the other hand, regarding the characteristics of cycle time and ergonomics, is each of nine vectors $v_{hi,ce}^{(1\text{-}9)}$ and $v_{mi,ce}^{(1\text{-}9)}$. They contain the average evaluation of all selected criteria of cycle time and ergonomics assigned to the nine categories. $v_{hi,ce}^{(1\text{-}9)}$ and $v_{mi,ce}^{(1\text{-}9)}$ are subsequently provided in the weighting 1 with the share in the nine categories in the total assembly task. The latter are calculated from the user inputs N_1 and N_2. For the first weighting, the percentages of the operations within the categories are calucalted, e.g.

$$w_{cg1} = p_{manual} \cdot p_{handling,human},$$

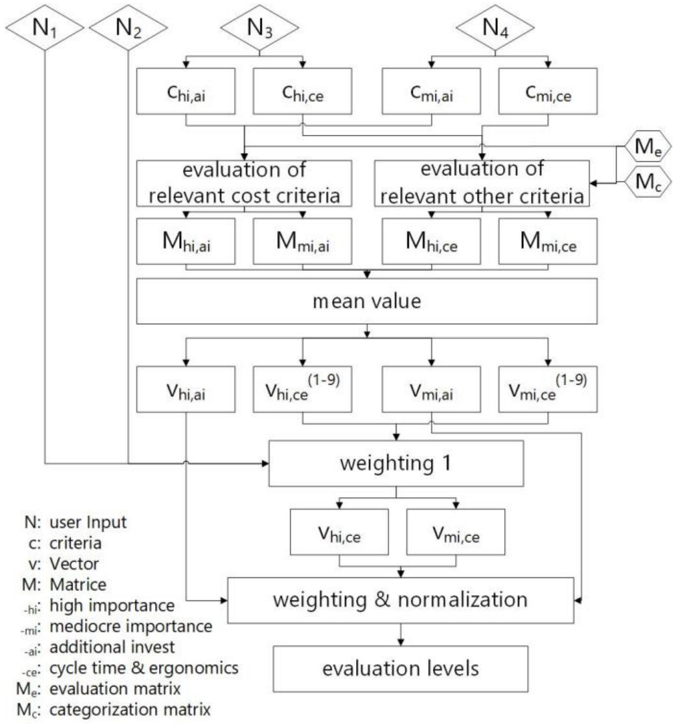
where w_{cg} is the weighting for a category and p is the percentage from the user input.

Following, each vector representing one category is multiplied with the weighting and all resulting vectors are added resulting in the vectors $v_{hi,ce}$ and $v_{mi,ce}$.

The four vectors $v_{h,ai}$, $v_{hi,ce}$, $v_{mi,ai}$ and $v_{mi,ce}$ are subsequently subjected to two further weighting processes. Firstly, cycle time and ergonomics are weighted at 2/3 and additional investment at 1/3. Secondly, the high importance is attributed with 2/3 and the mediocre importance with 1/3. The weighting factor for the high importance criteria regarding the additional investment for example, results in:

$$w_{hi,ai} = \frac{2}{3} \cdot \frac{1}{3} = \frac{2}{9}$$

Thus, there result four weighted vectors by multiplication of the vectors with the weighting value: $w_{hi,ai} \cdot v_{hi,ai}$, $w_{hi,ce} \cdot v_{hi,ce}$, $w_{mi,ai} \cdot v_{mi,ai}$, $w_{mi,ce} \cdot v_{mi,ce}$. These four vectors, as well as the vectors regarding high importance and the ones regarding low importance are added. Thus, the result is one vector including all four vectors, one vector that represents the result for the high and one representing the low importance. By normalization of the resulting vectors, the capabilities are represented by values between 0 and 1, where 1 is a high capability.



3.3. Definition of criteria for the evaluation

For evaluating the nine layouts, 23 criteria for cycle time and ergonomics as well as seven for additional investment were identified. They partly base on literature and partly were identified based on a regarded use case. To ensure a high degree of objectivity, an evaluation measure was introduced for each criterion and quantified in the nine concepts. For the evaluation of a criterion, better/worse-judgements were applied based on these quantified evaluation measures, whereas the best layout receives the level 1 and the worst 0.

The first six criteria consider several aspects of cycle time and ergonomics. First, the available workspace (c_{01}) and the movement length during material supply (c_{02}) are evaluated. Second, gripping paths over 40 cm (c_{03}), material supply above heart level (c_{04}) or additional body movements during material handling (c_{05}) are taken into account. Finally, the horizontal viewing angle of the gripping area (c_{06}) is considered. (c_{01}: own criterion, c_{02}: Methods-Time Measurement (MTM)-1, c_{03}-c_{06}: [17]).

As the robot's moving length influences its execution time significantly [18], it is taken into account via the distance between the center of the robot's material and the rca in automation and parallelization (c_{07}) as well as in a manner similar to the cca in collaboration (c_{08}).

Thiemermann (2005) identified the robot's four main ergonomic process factors of relative distance, relative angle of approach, velocity, and acceleration, among which the first two aspects can be used for an evaluation as a function of the layout. The higher both factors are, the higher the selected ergonomic robot speed can be [4].

As the relative distance depends on the robot's trajectory and the human's motion, it is evaluated based on dominant movements and middle locations. The relative distance is only considered during parallelization and is evaluated separately in each of the four possible scenarios (Table 1).

Table 2: Criteria with respect to different combinations of human and robot action

Criterion	Human Action	Robot Action
c_{09}	Assembling at hca	Assembling at rca
c_{10}	Assembly at hca	Material handling
c_{11}	Material handling	Assembling at rca
c_{12}	Material handling	Material handling

Regarding the middle positions of both resources, the following assumptions are made: During assembly, the hands of the employee stay at the hca, and the robot's end effector is located at the rca. During material handling, the midpoint between the center of assembly and the place of delivery of the material of a resource is set as the middle location. Since the material for the human and for the robot in some layouts is provided in two places each, the distance of all possible scenarios was calculated as described, and the average of the resulting distances was used.

The relative angle of approach (c_{13}) is defined as the angle between the current vector of the robot's velocity and the current vector of distance between both resources [4].

For the evaluation, the position and velocity of the tool center point as well as the most exposed position of the employee are recorded. The human stays at the hca, and the robot moves from its material to the rca and back again on the same trajectory by way of a linear motion (Fig 5).

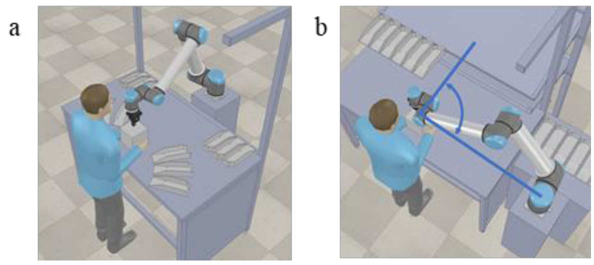


Fig 4: (a) small intrusion angle, (b) large intrusion angle

Furthermore, a connection can be established in collaborative mode between the freedom of movement of the human's hands and arms as well as the so-called intrusion angle. The latter is defined as the angle between the axis along the depth of the assembly table and the connection between the robot base and the cca. (Fig.3) shows a possible scenario of collaborative operation at a small (a) and large (b) intrusion angle, with the product being represented by a gray cube. While the small intrusion angle leaves a high degree of freedom of movement, the range of motion of the right arm and the right hand is noticeably restricted, especially in the vertical direction, and it has a large intrusion angle. As the angle of intrusion increases, it is therefore assumed that the robot places a greater limitation of the employee (c_{14}).

Layouts with separate hca and cca require additional body movements, which layouts with a combined hca and cca do not require (c_{15}). For the latter, an additional handling operation may be necessary if the worker is prevented from carrying out the assembly operation due to the product remaining at the cca. Therefore, criterion c_{16} differentiates between no restriction, a freely selectable direction of the additional handling process, and an additional handling process limited by small carriers.

Moreover, the effort and freedom in programming the robot is estimated on the basis of the collision potential of the robot with existing objects. On the one hand, the distance between the next collision object and the cca (c_{17}) and the rca (c_{18}) is evaluated. On the other hand, the distance between the robot and the next collision object is evaluated while the robot remains at the cca (c_{19}) and the rca (c_{20}).

In addition, a criterion is introduced which assesses the flexibility with which the robot can perform assembly activities on the product during collaboration (c_{21}), e.g. automation and parallelization (c_{22}). For this purpose, it is estimated how many surfaces the robot can orthogonally approach on a cube situated at the cca (c_{21}) and rca (c_{22}). If not all of the five surfaces are accessible, then the employee has to perform an additional product handling step if an inaccessible side is to be processed by the robot.

The accessibility of the workstation applied by [4] was transferred to the generated layouts (c_{23}) as the final criterion for cycle time and ergonomics.

The criteria for the additional investment are the space requirement (c_{24}), the necessity of additional tables (c_{25}) and additional elements (c_{26}) for material supply, and the required number of material deliveries (c_{27}). Also considered is an application of the evaluation carried out by [4] on the product neutrality of the plant structure (c_{28}) and expandability (c_{29}) as well as the possibility of integration in assembly systems (c_{30}).

4. Evaluation

The evaluation scenario is an assembly of a miniature transmission. It consists of the following parts: transmission bottom, gear wheel shaft, seal, transmission top and sensor. The

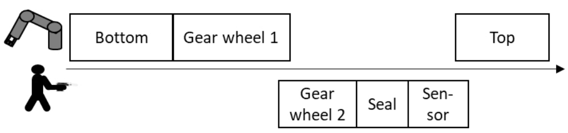


Fig 5: Task allocation for use case

assembly tasks are allocated to a human and a robot based on the properties of the product and the capabilities of the resources as shown in Fig. 6.

One of the user inputs N_1 is the distribution of the operation modes. For the use case, it results in 15% manual, 75% automated, 5% parallel, and 5% collaboration. (Fig. 7).

User input N_2 describes the percentages of assembly and handling tasks. There are 57 % of handling tasks and 43 % of assembly tasks for the robot. The human's tasks split into 64% of handling and 36% of assembly tasks.

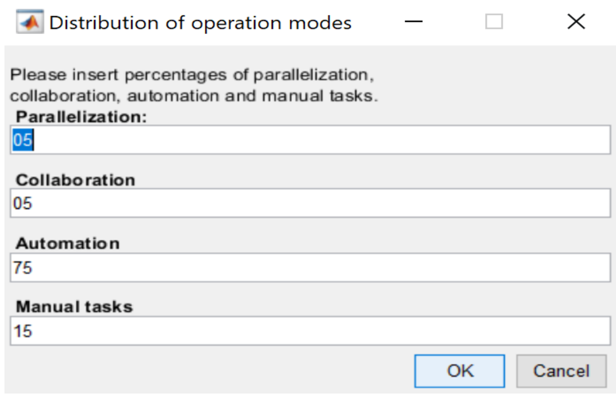


Fig 7: Interface for the input of operation modes

The defined criteria for the evaluation include the following:

Table 3: User defined criteria for evaluation

Importance	Criteria
High	c_{05}, c_{07}, c_{08}, c_{24}
Mediocre	c_{02}, c_{03}, c_{04}, c_{06}, c_{25}, c_{26}

Given the user inputs and the chosen criteria, the evaluation is conducted according to Fig. 4. The result of the method is an overview of the different layouts along with their capabilities.

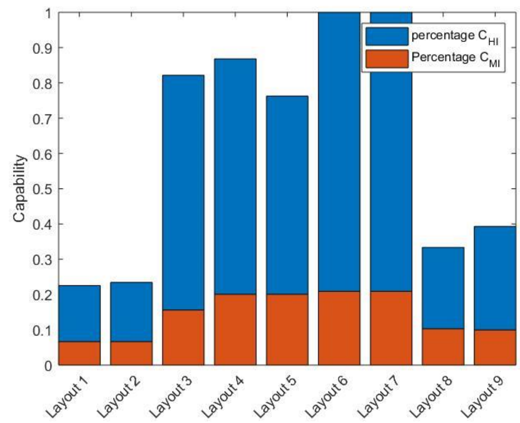


Fig 8: Result of the layout evaluation

For the evaluation of the results, the best-graded layout was compared to the worst-graded layout using a simulation with v-rep. The cycle times of both layouts were compared in this simulation. It shows that the cycle time of the worst layout layout was 84 seconds, whereas the cycle time of the more favorably graded calculated at 92 seconds, which gives a difference of 8 seconds and is equivalent to an improvement of approx. 9 %.

5. Summary and Outlook

This paper presents an approach used in the evaluation and comparison of layouts for a human-robot-collaboration in order to find the most suitable layout for the assembly of a certain product. 30 criteria were identified for the evaluation. These criteria include criteria also used for manual assembly, such as the grasping length as well as criteria applied to the robot, such as the grasping length for the robot. Furthermore, there are criteria with respect to the collaboration, such as the freedom of movement of the human's hands and arms. In the evaluation method, the user sets inputs in order to find out the most favourable layout.

In subsequent work, the identified criteria will be further evaluated in consent with experts regarding the planning and application of human-robot collaboration. Moreover, safety and ergonomic aspects shall be regarded and integrated. Also, the method will be enhanced for the use of different robot types. Some criteria will have to be adjusted for this purpose.

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