eng

Article

Assessing the Suitability of Automation Using the Methods–Time–Measurement Basic System

Malte Jakschik [1,*], Felix Endemann [1], Patrick Adler [1], Lennart Lamers [2] and Bernd Kuhlenkötter [1]

[1] Chair of Production Systems, Ruhr-University Bochum, Industriestraße 38c, 44894 Bochum, Germany
[2] Production Automation, RIF Institute for Research and Transfer e. V., Joseph-von-Fraunhofer-Straße 20, 44227 Dortmund, Germany
* Correspondence: jakschik@lps.ruhr-uni-bochum.de; Tel.: +49-234-32-24611

Abstract: Due to its high complexity and the varied assembly processes, hybrid assembly systems characterized by human–robot collaboration (HRC) are meaningful. Suitable use cases must be identified efficiently to ensure cost-effectiveness and successful deployment in the respective assembly systems. This paper presents a method for evaluating the potential of HRC to derive automation suitability based on existing or to-be-collected time data. This should enable a quick and favorable statement to be made about processes, for efficient application in potential analyses. The method is based on the Methods–Time–Measurement Basic System (MTM-1) procedure, widely used in the industry. This ensures good adaptability in an industrial context. It extends existing models and examines how much assembly activities and processes can be optimized by efficiently allocating between humans and robots. In the process model, the assembly processes are subdivided and analyzed with the help of the specified MTM motion time system. The suitability of the individual activities and sub-processes for automation are evaluated based on criteria derived from existing methods. Two four-field matrices were used to interpret and classify the analysis results. The process is assessed using an example product from electrolyzer production, which is currently mainly assembled by hand. To achieve high statement reliability, further work is required to classify the results comprehensively.

Keywords: process automation; MTM-1; degree of automation suitability; human–robot collaboration; HRC

check for updates

Citation: Jakschik, M.; Endemann, F.; Adler, P.; Lamers, L.; Kuhlenkötter, B. Assessing the Suitability of Automation Using the Methods–Time–Measurement Basic System. *Eng* **2024**, *5*, 967–982. https://doi.org/10.3390/eng5020053

Academic Editor: Antonio Gil Bravo

Received: 23 April 2024
Revised: 14 May 2024
Accepted: 15 May 2024
Published: 24 May 2024

1. Introduction

Identifying automation potential can help standardize production processes, ensure quality, and reduce dependence on skilled workers. In the context of electrolyzer assembly, there are currently many manual activities. Added to this is the increasing shortage of skilled workers and the conflict of interest in filling monotonous, repetitive tasks with qualified personnel [1]. For a competitive assembly of such systems in Germany as an industrial location, there is a need for optimization in the development, manufacturing, and assembly processes [2].

One of the most established methods for time optimization in the production environment is the Methods–Time–Measurement (MTM). It can be used to determine and analyze times of the current actual situation and to determine planned times for optimized processes or a changed working method [3].

In addition to time optimization, increasing automation in the production process to raise efficiency is possible. Using the previously determined time data for an automation suitability test creates further synergies in the engineering process. Currently, there is a high degree of automation in manufacturing, whereas humans mostly perform the assembly processes. The high percentage of human activities during product manufacture makes up to 20% of the overall costs. The efficiency of planning and performing such processes must increase to reduce it [4].

Due to the high variability and complexity of the products, automating the entire assembly process is very demanding. An industrial robot as a production system is highly flexible for automation. Still, it cannot yet keep up with human dexterity in many applications, even depending on the tool used. Hybrid production could be one of the viable solutions in which robots and humans cooperate or work together in the same workspace [5]. Assessment of automation suitability is currently reserved for automation engineers or system integrators, which is time-consuming and costly. As described above, the use of MTM time data analysis is widespread, making it desirable to derive automation suitability based on these data.

1.1. Structure of the Article

Motivated by the abovementioned situation, this paper presents a procedure model for identifying HRC potential based on MTM-1. This allows the data previously collected for time optimization to be further used for automation suitability. For this purpose, a classification of existing methods and work in the state of the art (Section 2) is first given before Section 3 describes the developed method in detail. The process is then evaluated using an example product (Section 4) before the results are summarized in Section 5. Finally, an outlook and potential for further work are given in Section 6.

1.2. Requirements for the Procedure Model

Based on the challenges described above, requirements can be derived for developing the method and can be divided into three categories: (1) model structure, (2) method, and (3) results.

- To develop the model and enable a systematic approach for transparent results, an iterative and step-by-step approach and a description of the current situation should be provided. (1)
- Furthermore, due to the complexity of the assembly processes described above, the model should focus on the HRC and the assembly processes, considering the performance capabilities of humans and robots. (1)
- The method must include the possibility of a knockout (K.O.) criterion for HRC so that the evaluation can be terminated directly to prevent unnecessary planning processes. (2)
- Time measurement, more specifically the use of MTM, is necessary to ensure industry adaptability due to the method's high prevalence. (2)
- In addition, the method's evaluation criteria must be transparent regarding the suitability of the automation or the HRC for good reproducibility. (3)
- Finally, the results should be transparent and comparable next to economic efficiency. (3)

2. State of the Art

As described above, MTM is one of the most established methods for time optimization. Redundant movements can be eliminated by using MTM-1, workflows can be adapted, and ergonomic conditions can be optimized. The method focuses on optimizing the design of the work system from the outset. Waste is to be identified and avoided across the entire value chain with the help of method planning in line with the lean philosophy. While the lean concept focuses on the internal value stream, the global value flow, and the efficient design of value chains for industrial goods, MTM concentrates primarily on optimizing workstations [6].

The description, structuring, planning, and analysis of workflows are based on process modules defined in terms of topic and time, summarized on the MTM data cards. The values taken from the data card are all given in the time unit "Time Measurement Unit" (TMU); 1 TMU corresponds to 0.036 s, 1 h to 100,000 TMUs. The starting point is based on the MTM-1 basic system, which enables the modeling of the manual workflow by required basic movements. These movements are reaching (R), grasping (G), moving (M), positioning (P), releasing (RL), disengaging (D), applying pressure (AP), turning (T), body, leg, and foot movements, and eye functions. Depending on defined parameters, standard times are assigned to each basic movement [3].

Several methods exist in the literature and industry to identify the potential for optimized assembly. Design for Assembly (DFA) in general and Design for Automatic Assembly (DFAA) are topics that have been extensively studied, and four methods have become established in the industry. The methods of *Boothroyd and Dewhurst* (*B&D*), *Lucas*, *Hitachi* (*AEM*), and the *modified Westinghouse* method are the most used. DFA or DFAA deals with how a product must be optimally designed for a well-automatable process. For that, the methods define various evaluation criteria to evaluate the suitability of automation. In specific further developments, the methods and the requirements described therein are combined in different constellations to consider better suitability of the method in connection with the product under consideration [7–13].

In addition, multiple methods for evaluating or introducing HRC have been identified in the literature. The following presents both model variants and shows the suitability of each approach.

2.1. Evaluation Methods with the Scope of an Assembly-Friendly Product Design

As described above, four established methods in the industry evaluate the product design in the context of the suitability for assembly. The overarching aim of the *B&D* method is to reduce costs by saving time during the handling and assembly processes. This is achieved by reducing the number of components within the assemblies [14,15].

The *Lucas* method is subdivided into three separate analyses and is based on a relative scoring system. In contrast to the *B&D* method, the functional analysis is used for early design analysis. Not all design questions must be fully answered at the time of application. The components are categorized into two groups: essential and non-essential components. Non-essential components should be eliminated to reduce the number of components to a minimum [16].

The *Westinghouse* method calculates product complexity using the assembly time, a complexity factor, the assembly time value, and the part efficiency. As in the previous methods, the complexity is determined using predefined influencing factors, resulting in the assembly time value. For the assembly time, the processes are classified as reaching, gripping, and bringing, and the process itself and the assembly time are calculated [17]. The *modified Westinghouse* method simplifies and differs from the superordinate method in creating the joining sequence diagram and eliminating non-essential components [9,13].

These methods are designed to identify weak points in the product design. However, this approach focuses on the assembly processes to identify tasks for humans and functions with a high automation potential. The *Hitachi-AEM* is categorized as an evaluation method for the assembly process [9,13,18]. According to the Hitachi AEM, two key figures are determined and evaluated to assess the product design. On the one hand, the complexity of the handling and assembly processes is determined using the evaluation factor E. On the other hand, the cost evaluation factor K is used to determine the savings potential through the optimized product design. As with the methods described above, predefined operations are used to classify and evaluate upcoming processes to estimate the handling and assembly effort. In contrast to the *B&D* and *Lucas* methods, the *Hitachi AEM* does not differentiate between a manual and an automated assembly because of the strong correlation between an assembly-friendly product design and the resulting simplified assembly [13]. With that in mind and the presented approach of an optimal distribution of the assembly task, this method is unsuitable for that procedure model.

The *MTM ASSOCIATION e.V.* has developed a method (*ProKon*) to minimize the costs during product development. It evaluates the assembly effort and focuses on low-cost solutions through targeted modification of parameters that the designs can influence. The procedure is divided into seven steps. The first step is remarkably similar to the methods described above, whereby various evaluation criteria such as weight, material, geometry, or specific handling conditions are analyzed. This is followed by the determination of the assembly processes. In step three, the assembly position of the individual parts is determined on the assumption that the parts to be assembled are not in an optimum state of order. After that, in step four, the individual parts and higher-level assemblies are then evaluated by an evaluation matrix. This matrix differs from the card in that it analyzes the time estimation of the assembly process. Steps 5 to 7 deal with optimizing the product design, which is outside this approach's scope and is therefore not considered in more detail [3].

Since *ProKon* focuses on an assembly-friendly product design and process and does not distinguish between an automated or manual assembly task, this method does not fit this approach as well as the methods before.

2.2. Evaluation Methods with the Scope of Human–Robot Collaboration

Bauer et al. present a procedure model based on a cost-effective identification of practical HRC applications developed by the Fraunhofer Institute for Industrial Engineering (IAO). The model is divided into three steps and focuses on avoiding large volumes of data. Despite its simple structure and application, individual company goals are considered. In the first stage, assembly system data are analyzed for the three fundamental areas of classic system planning data: the problem situation, the degree of preparation of material provision, and potentials. The second stage is planning data at the workstation level, and potentials are considered. Finally, the last step is evaluating the process and product level. Subsequently, the assembly processes with the most significant automation potential can be selected, and HRC solutions can be implemented based on the preselection and evaluations [19].

Weber and Schüth developed a model for introducing HRC. It is structured on a step-by-step basis and is intended to enable companies to prioritize the factors to be checked successively. The focus shifts from the process to the product to the resource regarding HRC suitability. The first three steps consider component orientation, gripping properties, temperature, or flexural rigidity. In addition, the method evaluates the workstation and training needs. It concludes with an assessment of economic efficiency [20].

The model approach developed by *Petzold* et al. is divided into five steps. It defines six requirements for analyzing the potential for the use of HRC: specific focus on industrial assembly activities, method-supported analysis and evaluation, strong process orientation, consideration of quality, evaluation of economic efficiency, and consideration of ergonomics. The authors use MTM in their model approach for the assessment of economic efficiency but not for the identification of potential processes to be automated. To evaluate the use of HRC, both the assembly processes and the product design and geometry are considered [21].

The SafeMate method was developed to quickly and intuitively identify and assess the potential for using HRC. The research project of the Institute of Assembly Technology and the Institute of Production Systems and Logistics at the University of Hanover is intended to serve as a guideline for safe and accepted HRC implementations in companies. The SafeMate method consists of two successive stages. In the first stage, the added value of the HRC application is assessed, while the second stage evaluates the technical implementation [22].

The KoMPI Quick Check was also developed as part of a research project and focused on creating a new method for the integrated planning and realization of collaborative workstations for variable production scenarios. It is used to assess and identify HRC potential. This method, divided into three levels, uses a point system based on process criteria for evaluation. A good knowledge of the evaluated work system is a prerequisite. No other special prior knowledge is required [22,23].

Linsinger et al. present a method that identifies the suitability of HRC potentials in five steps. Step 1 begins with an overall analysis of the assembly system and is supplemented by a detailed examination in step 2. Here, the individual stations are analyzed using cycle time analysis and a checklist to assess their technical suitability. This depends on various factors, such as the dimensions and geometric characteristics of the product or the supplied assembly part. The assembly station with the highest HRC potential is then analyzed in step 3. This analysis focuses on determining the division of labor between robots and humans. It uses the checklist described above and the MTM-1 for this purpose. Steps 4 and 5 deal with the application scenarios' design and implementation planning [24].

Teiwes et al. present a method to identify the HRC potential in automotive assembly lines based on the MTM Universal Analysis System (UAS). The authors describe their approach in three steps. Step 1 evaluates the automation potential for each movement within the assembly. For this purpose, each module of the MTM UAS is assigned a degree of automation potential based on the description of each module. The value determined from this is multiplied by the frequency of the activity in step 2. The final step summarizes the values to obtain an overview of the assembly line [25].

2.3. Classification of Described Literature

The literature will be categorized based on the state of the art presented and the previously derived requirements. This results in the following analysis shown in Scheme 1. Overall, no model in the literature meets all the requirements for this approach. Although the model structure and result categories fulfill the requirements placed on the model in various constellations, deviations from the requirements can be identified in the fulfillment of category 2. In particular, the combination of MTM time data analysis and the consideration of a K.O. criterion cannot be found in existing approaches.

Legend:

o → not fulfilled
• → partially fulfilled
•• → fulfilled

■ (teal) → model structure
■ (orange) → methodology
■ (red) → results

		DFA					HRC						
		Authors / Models											
		Boothroyd & Dewhurst (1987)	Lucas (1989)	Hitachi AEM (1990)	Modified Westinghouse Method (1989)	ProKon	Bauer et al. (2018)	Weber und Schüth (2020)	Petzold et al. (2021)	SafeMate Hees et al. (2019)	KoMPI-Quick-Check Ermer et al. (2019)	Linsinger et al. (2018)	Teiwes et al. (2016)
Categories		**Requirements**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**11**	**10**	**11**
1	**A1**	Step-by-step procedure	••	••	••	••	••	••	••	••	••	••	••	••
	A2	Iterative procedure	••	••	••	••	••	o	o	••	o	o	o	o
	A3	Presentation of the current status	•	•	•	•	••	••	••	••	••	••	••	••
	A4	Focus on HRC	o	o	o	o	o	••	••	••	••	••	••	••
	A5	Focus on assembly processes	•	•	••	••	••	••	•	••	••	••	••	••
	A6	Consideration of the strengths and weaknesses of human and robots	•	•	•	•	o	••	•	••	•	•	••	o
2	**A7**	Knockout Criterion for HRC	o	o	o	o	o	o	o	o	o	••	o	o
	A8	Time data determination	••	o	o	••	••	•	o	••	•	•	••	••
	A9	Usage of MTM-1	o	o	o	o	••	o	o	••	•	o	••	••
	A10	Transparent evaluation criteria	••	••	••	••	••	••	•	••	•	••	•	••
3	**A11**	Clarity and comparability of the results	••	••	••	••	••	••	•	•	•	••	••	••
	A12	Evaluation of the economic efficiency	••	o	o	•	•	••	••	••	••	o	••	•

Scheme 1. Analysis of relevant valuation models in DFA and HRC [3,9,14,16,18–25].

With that in mind, the comprehensive development of a procedure model that fulfills all requirements is described below. Individual aspects and methods from the previous analysis are incorporated into the process model as steps are developed in-house. A detailed explanation of all aspects of the process model ensures a comparatively simple and transparent application. However, prior knowledge of performing an MTM-1 analysis is required.

3. Modelling of MTM-1 on HRC

The developed procedure model, derived from the state of the art described above, provides the potential of HRC based on MTM-1 and is divided into eight steps (Figure 1).

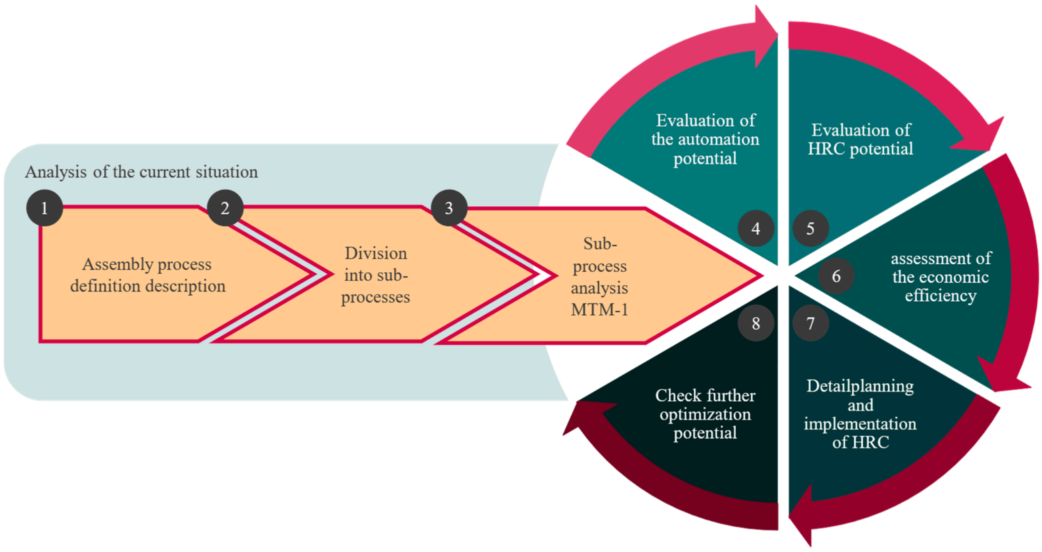


Figure 1. Structure of the presented model approach MTM-1-HRC.

The evaluation starts with analyzing the actual state (steps 1–3). Here, the assembly processes are defined, and the system is described in detail. The processes are then structured into sub-processes (SPs) before they are analyzed using MTM-1, which already corresponds to the current state of the art in using predefined motion time systems by many industrial users. For this reason, steps 1–3 can also be skipped for existing MTM-1 analyses, and existing data can be used. In step 4, the evaluation model MTM-1 is expanded to include an evaluation system determining the automation potential. The HRC potential is evaluated in step 5 before an economic efficiency assessment is performed (step 6). After a successful profitability check, the seventh phase involves detailed planning and HRC implementation. Finally, step 8 checks the assembly process for further optimization potential. For this purpose, processes with high time requirements and low suitability for automation are considered. Additional optimizations can consist of adjustments to the provision of parts and tools or pick-up options, path changes, or joining aids. After the completion of phase 8, an iteration occurs, starting with phase 4. It should be noted here that in the case of extensive process optimizations from the previous iteration, a new analysis of the process using MTM-1 can also be helpful. This results from adjustments to the workstation and new divisions of the processes, resulting in a different process and new MTM codes. In this case, the iteration starts in phase 2 or 3.

3.1. Analysis of the Actual State

The assembly processes are described in a process profile based on the MTM analysis [3]. The overall work task, including a brief process description, is recorded, and the workstation is defined. The structure of the workstation, as well as size and distance information, are particularly relevant. This step also includes a detailed explanation of the process or assembly result (output). Furthermore, all individual parts, machines, tools, and any means to facilitate the assembly process (input) are recorded. For complex assembly processes, the second phase divides the main overall work task into several individual SPs. Each SP fulfills a task within the overall process.

A coding technique is developed for uniform identification of the SPs, which is based on the 12-digit code of the MTM system but has been shortened and simplified. As this code is only used for error-free identification and is similar in principle to the existing code of the MTM system, the functionality of the code is not explained further here. After that, the SPs are analyzed by the MTM-1. The MTM-1 basic system is used, as it serves as a basis for other MTM systems and enables a high resolution or detailed activity descriptions using the numerous basic movement modules. For that approach, its formula has been extended by the column of the suitability of automation (Scheme 2).

MTM-1 HRC Analysis								
No.	**Description (L)**	**N x F (L)**	**MTM-1 Code (L)**	**TMU**	**Degree of automation**	**MTM-1 Code (R)**	**N x F (R)**	**Description (R)**
				0	0			
				0	0			
				0	0			
				0	0			
		0	Gesamt	0	0		0	

DAS x (N x F):	0
Overall N x F:	0
Prelimainary average/ degree of automation:	0.00
Variance:	0.00
Standard deviation:	0.00
K.O. citeration evaluation factor:	1
Complexity factor:	0
Final average/degree of automation:	**0.00**

Scheme 2. Excerpt from the MTM-1-HRC Excel template based on the MTM analysis [3].

The individual time requirements are calculated based on the MTM-1 code, which describes the process step using the granular movement modules described. Double-handed tasks and similar restrictions for parallelization are also considered automatically. Behind this code, time requirements are stored so that at the end of the MTM analysis, the results show processes with a high optimization potential. Aspects such as long distances, many tasks with a high time requirement, or feeding of parts with an unknown orientation are made visible for short-term optimizations.

3.2. Evaluation of the Automation Potential

To evaluate the automation potential, the MTM-1 formula is extended by the column for the degree of automation suitability (DAS). It is important to note that this approach evaluates the potential of complete automation (step 5), a coexistence, or a synchronized assembly process regarding the requirements of HRC (step 6). The potential of the latter two will be described in the next section. Automation suitability is evaluated using a Likert scale with a point scale from zero to three, where high suitability is indicated by a three. In this approach, in addition to the time requirements, the automation capability ratings of the individual granular motion modules were also derived from the MTM-1 code. For this reason, the criteria used to assess the suitability for automation are also heavily dependent on the descriptions of the MTM basic movements, as found in the data cards [3].

If individual tasks are rated zero in terms of DAS, the entire SP is classified as non-automatable and is to be regarded as the required K.O. criterion. The same applies if at least three activities are assessed with one point. To evaluate the individual tasks regarding suitability for automation, evaluation criteria are defined that consider, among other things, the strengths and weaknesses of a robot as well as economic aspects. The approaches described in Section 2 have different combinations of evaluation criteria for automation suitability. Still, they all have in common that they are based on the four established methods. Due to the link with the MTM-1 code, the evaluation criteria are not to be understood as rigid but based on the cases depicted in the MTM-1 method. Nevertheless, the requirements described by the MTM cases can also be assigned to the methods mentioned, as you can see in Scheme 3. The established methods focus on the product design and its assembly; in addition, this approach rates the assignment of tasks between humans and robots so that the criterion of accuracy was added.

o → not considered
● → partially considered
●● → considered

		Authors / Models				
		Boothroyd & Dewhurst (1987)	Lucas (1989)	Hitachi AEM (1990)	Modified Westinghouse Method (1989)	ProKon
Categories	**Evaluation criteria**	**1**	**2**	**3**	**4**	**5**
EC1	Range of movements	o	o	o	●●	o
EC2	Accessibility	●	●●	o	o	●●
EC3	Gripping operations	●	o	●	●	o
EC4	Weight	o	●	o	o	●●
EC5	Orientation	o	●●	o	●	o
EC6	Handling	●	●●	●	●●	o
EC7	Symmetrical joints	●	●●	●	o	●
EC8	Tolernace	o	o	o	o	●
EC9	Accuracy	o	o	o	o	o

Scheme 3. Assignment of selected evaluation criteria [3,9,14,16,18].

Movements over a more than 60 cm distance reduce the DAS by one. Longer distances are associated with increased effort or require a large, more cost-intensive robot replacement. How objects are approached and the different gripping movements are further criteria summarized under EC2.

Industrial robots can easily approach and pick up a single, easy-to-grasp object that is always in the same place (DAS = 3). Both grasping grips, touch grips, and transfer grips are possible. If the location of these objects changes, for example, when removing them from a pallet, additional programming must be carried out for precise positioning. Alternatively, coarse object recognition can be implemented, e.g., using a camera or sensors on the gripper. The evaluation factor is, therefore, reduced by one. For tiny (smaller than 3×3 mm^2) or fragile objects, increased financial expenditure must be expected for special grippers, sensors, and precise calibration. Gripping operations are like the need to reposition an object and are assessed under EC5.

The maximum load-bearing capacity of such robotic systems is a limiting factor in evaluating HRC suitability. Handling weights over 10 kg is regarded as an aggravating factor and leads to a reduction in the DAS by one. Moreover, handling, in general, is an essential factor in the suitability of automation. For example, parts that are difficult to grip, flexible, or oily make special programming necessary or may require gripper or robot adaptation. Difficult access to a part to be separated or a joining location diminishes the automation capability. In addition, the maximum travel speed of the robot can be negatively affected. For example, when joining or separating, this is considered by subtracting one point from the suitability for automation.

Depending on the fit class, symmetrical joints pose no difficulties for automation (DAS = 3). Semi-symmetry allows several joining positions, and the robot can only make minor alignment corrections. Thus, no points are deducted for this symmetry case. In the case of non-symmetry, on the other hand, some significant alignment corrections and a fixed joining position require increased effort on the part of the robot. Therefore, a maximum of two points are awarded for this characteristic.

With a loose fit class, there are no restrictions on automation suitability. Tight fits and joining tolerances can only be achieved with time-consuming calibration, hence minus one. Cases with fixed fit classes and, therefore, optionally low joining tolerances or high force requirements, are generally regarded as K.O. criteria and given zero points. Similarly, insertion and the associated application of pressure for fits are assessed. The need for a highly accurate process also impacts the DAS and is assessed under the last criterion of accuracy.

All other MTM-1 process modules whose actions can be carried out by a robot without complications or additional effort, e.g., simple gripping movements, releasing objects, light pressure, etc., receive three points and are rated with the highest suitability for automation.

To obtain an overall DAS, the column of suitability is multiplied by the corresponding values from the column of the "number and frequency (N $\times$ F)". The sum of all values and the subsequent division of it by the total number is used to calculate the provisional average and, thus, the provisional DAS. A high average indicates a high potential for automation, while a low value implies the exact opposite. Furthermore, the standard deviation is determined considering the respective variance. This serves to verify and refine the assessment, to identify potential "outliers", and to assess the suitability of HRC subsequently. Figure 2 uses a four-field matrix to illustrate the potential result areas and provides instructions for the next steps.

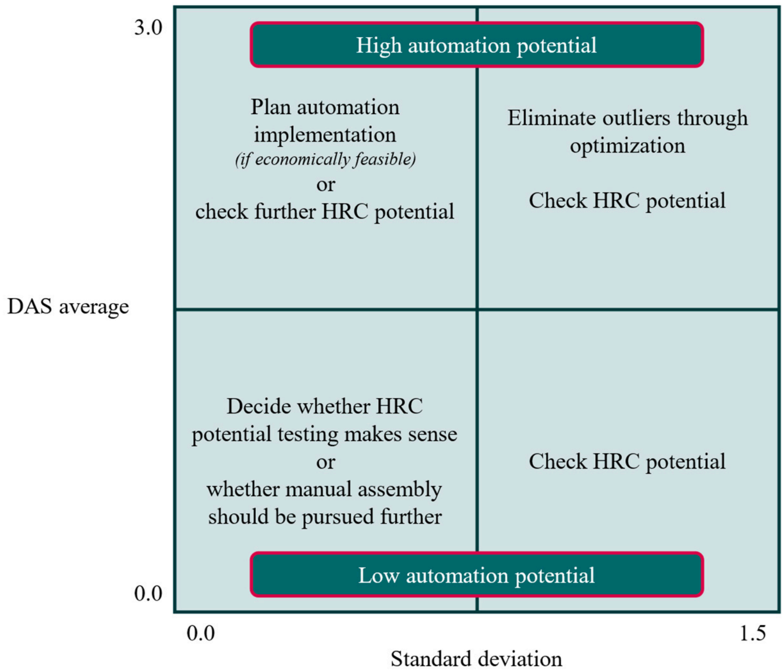


Figure 2. Four-field matrix to classify the potential of automation.

The SP under consideration should be in the second quadrant for suitable automation suitability. SPs in the first quadrant are outliers and should first be attempted to be minimized. The two lower quadrants indicate a low DAS, whereby the HRC potential should be investigated further in all cases.

3.3. Evaluation of the Human–Robot Collaboration Potential

In step 5, the HRC potential and allocation of labor is determined. The test is carried out in two stages:

1. Allocating the activities of the SP to humans and robots and subsequent testing of the changed DAS.
2. Testing of possible simultaneous execution of the activities.

Considering the strengths and weaknesses of humans and robots, the tasks of an SP are divided between these two actors. Activities with a low DAS are assigned to a human, and those with a high DAS are assigned to a robot. The human activities are entered on the left, and robot activities are on the right. For all activities classified as "manual", the automation suitability factor is deleted from the MTM-1 analysis. The updated final automation suitability level is then compared with the original value determined from the previous phase. If there is no significant improvement or a substantial imbalance in the allocation of tasks between humans and robots (greater than 75:25), the allocation is discarded. If there is a significant improvement in the value (average greater than two points) and no such imbalance in the allocation, there is a high HRC suitability.

Based on the previous interpretation of the results, the HRC potential is also depicted in a four-field matrix (Figure 3).

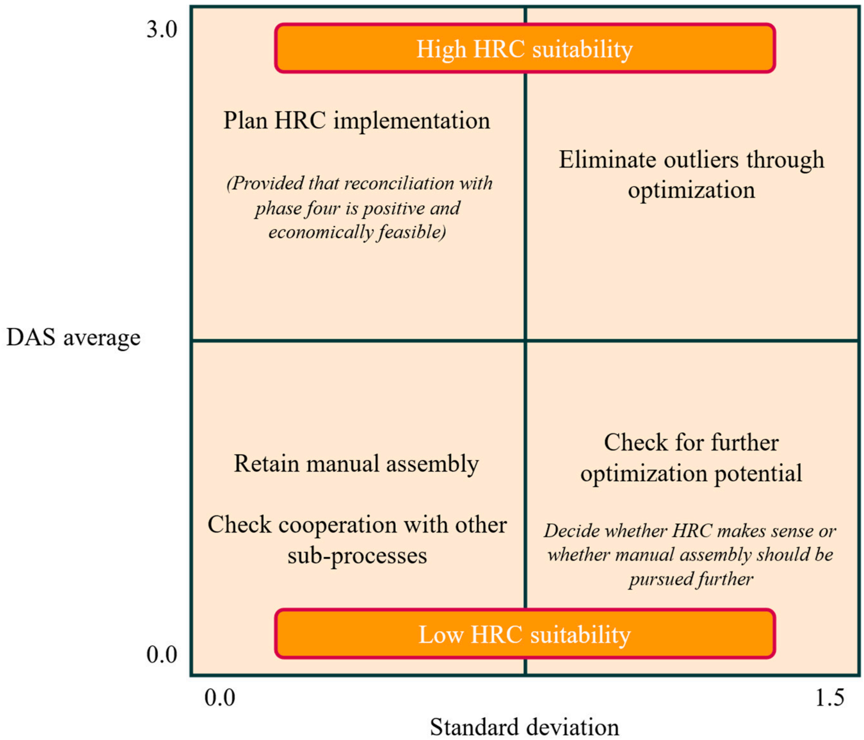


Figure 3. Four-field matrix to classify the HRC potential.

Depending on the characteristics of the final average or the DAS and their standard deviation, a result classification is made possible, and instructions for further procedures are derived.

3.4. Assessment of Economic Efficiency, Detailed Planning, and Optimization Potential

When applying the procedure model described here or from previous MTM 1 analysis, the respective times for the described SPs are available, based on which an economic application can be examined. For this purpose, the investment costs are compared with the expected productivity effects and time savings. Here, the total MTM times of the MTM-1 analyses are used as a basis, and the original actual times (before HRC) are compared with the planned times (after/with HRC). A subsequent amortization calculation provides information as to the duration from which the investment is worthwhile and helps with the risk assessment.

Phase 7 of the process model includes detailed planning and subsequent HRC implementation; the qualified HRC potentials are implemented for the respective assembly process, and the introduction, including all measures, is planned. The employees are informed about the planned steps and, if necessary, involved in developing the workstation design. In addition, training on safety and the essential functions of the robots must be carried out. Depending on the type and scope of the HRC implementation, additional needs-specific qualifications may also be relevant.

Due to the high variability in assembly, further or new optimization potentials are examined after detailed planning and implementation. This focuses on activities in the respective analyses with high time requirement values or low suitability for automation. It is checked whether an improvement in the time requirement and the suitability for automation can be achieved through change measures. These can consist of further adjustments to the provision of parts and tools or pick-up options, path changes, or joining aids. In addition, scenarios with new cross-process automation solutions, e.g., acquiring additional machines, are considered in this phase. A redesign of the workstation is also possible. The process model is iterated to qualify further HRC potential. This begins with phase 4.

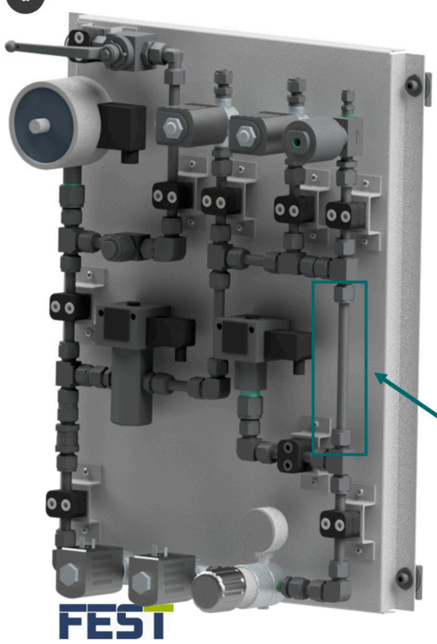
4. Evaluation Using the Industrial Example of Water Electrolysis

The evaluation focuses on selecting and qualifying HRC potential in an assembly process. A brief comparison of the time requirement values (before and after) is carried out based on phase 6. The subsequent realization or detailed planning and implementation (phase 7) is not dealt with further and would have to be investigated in the industrial context in additional work. Testing and optimization (phase 8), which involves the presentation of improvements as part of a cross-SP assembly, is not focused on here for the same reasons. The procedure for an MTM-1 analysis is not explained in detail. Therefore, the evaluation focuses on the first five phases of the developed process model.

In the context of electrolyzer production, instrument panels are required to control the process and ensure the quality of the processed media. Four different media are essential for the operation of electrolyzer systems, each requiring a different structure and composition of the panel. Figure 4a shows a customized nitrogen instrument panel, which is needed for purging the tubes for maintenance or emergencies. In addition, instrument panels differ in structure even with the same media, depending on the system size and customer. In summary, this product has a complex and very flexible product structure and is currently assembled by hand, as described in the beginning. Therefore, the product and the associated assembly processes are ideally suited as validation objects. Due to the frequency of the process, the focus of the evaluation is on the screwing of the tube elements.

The process is divided into five SPs, and the predicted time requirement is built by the sum of all time requirements (Figure 4b). Processes with high time requirements are time-consuming, cost-consuming, and need to be optimized. As there are already automation solutions for shortening pipes, the process with the second highest time requirement is considered, which is the screwing process. In addition to a tube, a double-ferrule fitting is required for a tight tube connection in the hydrogen context. Both must be taken from a stock and then joined together. The tube must be inserted into the fitting, and the nut must be tightened to assemble. The geometry of the screw connection component is like a standard hexagon nut. A tight connection is created when the nut is firsthand-tightened and then tightened by single ¼ turns, according to the quasi-industrial standard of Swagelok. The nut must be marked after hand-tightening for a subsequent visual check of the single ¼ turns. All in all, the process can be described by 32 basic movements and requires approx. 12 s in the MTM-1 prediction. In the following, the composition of the DAS for the ten superordinate classifications of basic movements for that SP 4 is shown in Table 1. The validation of the DAS is based on the assessment of the defined criteria, which are linked to the MTM-1 code. For example, the "reaching" process of category B is described as "Reaching out to a stand-alone counterpart that is located in a place that changes from work cycle to work cycle" [3] (p. 411), from which the evaluation criteria EC2, EC4, EC6, and EC9 can be derived. By adding the movement length to the MTM-1 code, the evaluation criterion EC1 can also be evaluated. The following basic movements can be interpreted similarly. As shown, the average of all fulfilled criteria has been calculated and rounded down to reflect the worst possible case. This ensures that the most transparent processes for automation suitability are identified first.

a



b

Structure of sub-processes				
Code		D.001.00		
Process name/ Worktask		Assembly of tube and tube srewing		
Start		Reaching towards a stack of pipes		
End		Release the assembled tube connection		
No.	**Description**	**Code**	**N x F**	**Overall TMU**
1	Separate and mark tube	C.001.01	1	133.5
2	Shorten tube	C.001.02	1	700.6
3	Rework the tube end with a deburring tool	C.001.03	1	130.8
4	Assemble tube with tube fitting	D.001.04	1	341.3
5	Carry out quality control with a test gauge	C.001.05	1	165.0

Figure 4. Nitrogen instrument panel (**a**) and associated process profile (**b**).

Table 1. Composition of the DAS (Extract) for the SP 4 under consideration.

	DAS	Average	EC1	EC2	EC3	EC4	EC5	EC6	EC7	EC8	EC9
R-B < 60 cm	2	2.33	3	2	\	3	1	3	\	\	2
G	3	3	\	3	3	\	\	3	\	\	\
M-C < 60 cm	3	3	3	\	\	3	\	3	\	3	3
M-B > 60 cm	2	2.80	2	\	\	3	\	3	\	3	3
R-A < 60 cm	3	3	3	3	\	3	3	3	\	\	3
P2SE	2	2.60	\	\	3	\	\	3	3	2	2
RL1	3	3	\	\	\	\	\	3	\	\	3
M-B < 60 cm	3	3	3	\	\	3	\	3	\	3	3
P1SSE	3	3	\	\	3	\	\	3	3	3	3
APA	3	3	\	\	\	\	\	3	\	\	3

As described above, the potential of the automation for the different SP is visualized in a four-field matrix (Figure 5a). The first four SPs exhibit a high potential for automation, whereas the SP 5 (quality testing) is categorized as "not automatable" based on the K.O. criterion. The lower suitability for automation in SP 4 compared to the first three SPs is mainly due to the high number of different activities and the associated high complexity factor. Points are also deducted for the vice clamping activities and two joining processes. Nevertheless, with a final average of 1.86 and a standard deviation of 0.31, SP 4 has a high automation potential.

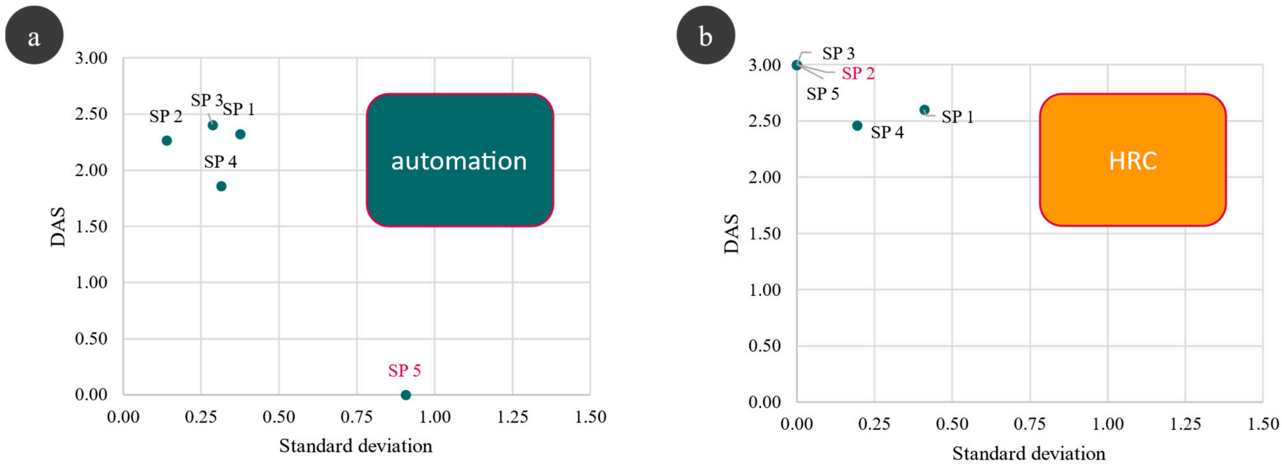


Figure 5. Potential of automation (**a**) and HRC (**b**) based on a four-field matrix.

Compared to the results from stage 4, the cooperative and collaborative HRC potential assessments show an improvement in the degree of automation suitability for all SPs (Figure 5b). Furthermore, allocating tasks between humans and robots eliminates the K.O. criterion for SP 5. All SPs have a high HRC potential. SP 4 has a complexity factor of 0.5 despite the division of activities and still loses one point in the analysis when moving to the tube fittings. Nevertheless, there is an improvement to an automation suitability factor of 2.46 and a standard deviation of 0.19. SP 4 has a high HRC potential. Table 2 shows the total time required for the process model's individual analyses of phases 3, 4, and 5, as well as the DAS for all SPs in the context of full automation and HRC. The reduction in the time requirements of the MTM-1 column and the Automation column results solely from the optimizations about picking up and storing items at the assembly station based on the MTM-1 analysis (phase 3) for a time improvement. The time required for the process modules for a fully automated solution is assessed as being equivalent to the time needed for manual activities. In SP 4, a reduction in time requirements of just under 9% can be achieved, corresponding to a time saving of approx. 1.1 s.

Table 2. Comparison of time requirements from the different phases.

Structure of Sub-Processes						
No.	**MTM-1 TMU**	**Automation TMU**	**Automation DAS**	**HRC TMU**	**HRC DAS**	**Total Time Saving**
1	133.5	117.0	2.82	91.5	2.60	42.0
2	700.6	697.3	2.76	691.7	3.00	8.9
3	130.8	127.5	2.90	127.5	3.00	3.3
4	341.3	336.7	2.86	309.9	2.96	31.4
5	165.0	164.8	2.31	164.8	3.00	0.2
Sum	1471.2	1446.3	-	1385.4	-	85.8

The considered assembly process of screwing together tube elements and all the SPs involved is highly suitable for HRC. However, the high values of the DAS are also due to the allocation of tasks, as the robot only has to work on suitable tasks here. Therefore, the average rating is also significantly better. The preferred form of interaction varies, as the evaluations of the different phases show. While SP 1 and SP 5 benefit from cooperative or collaborative collaboration, coexistence or synchronization should be selected for SP 2. SP 3 and SP 4 are suitable for all forms of HRC.

5. Conclusions of the Procedure Model MTM-1-HRC

The procedure model developed makes it possible to describe complex assembly processes and divide them into SPs. It is based on the basic MTM-1 modular process system, which is already used in many industries and companies of all sizes. The MTM-1 analysis is used to determine actual times and provides initial approaches for optimizations in assembly. In the subsequent MTM-1-HRC cycle, the SPs can be checked for suitability for automation and HRC. The different forms of HRC are considered in the various phases. The high level of detail of the model makes it possible to determine the respective suitability of the various activities based on the defined evaluation criteria and to identify individual problems or knock-out criteria directly. Criteria from established DFA methods are used and linked using the process description of the individual MTM-1 modules. In addition, the interpretation matrices support the classification of the analysis results and the evaluation of automation and HRC potentials. They provide information for further action. In a final investigation of further optimization potential, new and cross-process measures can be identified, and thus, approaches for new iterations of the process model can be derived. The developed process model can be seen as further developing existing models and fulfilling all requirements.

6. Outlook and Further Work

However, the model presented also has some potential for further development, which must be mentioned and addressed in subsequent work. To evaluate the time savings, the approach developed is based on the exact time requirements for both actors, humans and robots. However, humans are significantly faster than robots for various tasks, particularly in assembly. This results in a certain lack of precision in evaluating economic efficiency by comparing the time requirements. Furthermore, there is no linking of pre- and post-movements. This would be useful for an accurate assessment of the economic viability of implementing such automation solutions. In addition, the use of various tools such as screwdrivers or wrenches for the assembly process would become much more important. At this stage, the method presented evaluates the suitability of the individual components regarding automation. In the future, a holistic evaluation of the SP would be possible. One possible solution could be the rule base for multi-hand movements. As described above, MTM-1 considers the time estimation of human multi-hand movements. HRC could be considered as a further specification of this movement and could, therefore, be used to derive new rules and, thus, times. This connection must be investigated further.

It should also be noted that, although established criteria were used to assess the suitability of automation, the grading of the assessment is based on several assumptions that need to be further investigated and adjusted afterward with the help of a panel of experts. No distinction is made between autonomous industrial robots and collaborative robots, nor is there consideration of the respective size. Hence, the validity of the assumptions is questionable depending on the context of the application. Adjustments, e.g., to the robot accuracy, the movement radii, or the weight handling, would lead to changed evaluation criteria and thus differing degrees of automation suitability. For that, a more dynamic system for the evaluation criteria must be researched and implemented in the future. Moreover, comprehensive knowledge of the processes is required to apply this method. Therefore, the application area of this method lies in detailed engineering or the downstream optimization of existing production systems. However, basic engineering significantly impacts costs, so adapting this method for early use would make sense.

Author Contributions: Conceptualization, M.J., F.E. and P.A.; Methodology, M.J., F.E., P.A., L.L. and B.K.; Writing—original draft, M.J.; Writing—review & editing, P.A., L.L. and B.K.; Visualization, M.J. and F.E.; Supervision, B.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the German Federal Ministry of Education and Research (BMBF) under grant number 03HY114B within the research project H2Giga—HyPLANT100. Additionally, the authors acknowledge support by the Open Access Publication Funds of the Ruhr-University Bochum.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Smolinka, T.; Wiebe, N.; Sterchele, P.; Palzer, A.; Lehner, F.; Jansen, M.; Kiemel, S.; Miehe, R.; Wahren, S.; Zimmermann, F. *Studie IndWEDe: Industrialisierung der Wasser Elektrolyse in Deutschland: Chancen und Herausforderungen für Nachhaltigen Wasserstoff für Verkehr, Strom und Wärme*; NOW GmbH: Berlin, Germany, 2018.
2. Hebling, C.; Ragwitz, M.; Fleiter, T.; Groos, U.; Härle, D.; Held, A.; Jahn, M.; Müller, N.; Pfeifer, T.; Plötz, P.; et al. *Eine Wasserstoff-Roadmap für Deutschland*; Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe Fraunhofer-Institut für Solare Energiesysteme ISE: Freiburg, Germany, 2019.
3. Bokranz, R.; Landau, K. *Handbuch Industrial Engineering: Produktivitätsmanagement mit MTM*, 2nd ed.; Schäffer-Poeschel: Stuttgart, Germany, 2012.
4. Neb, A.; Göke, J. Generation of assembly restrictions and evaluation of assembly criteria from 3D assembly models by collision analysis. *Procedia CIRP* **2021**, *97*, 33–38. [CrossRef]
5. Linsinger, M.; Stecken, J.; Kutschinski, J.; Kuhlenkötter, B. Orts- und aufgabenflexibler Einsatz von Leichtbaurobotern in der Montage. *Wt Werkstattstech. Online* **2019**, *109*, 94–99. [CrossRef]
6. Becker, T. *Prozesse in Produktion und Supply Chain Optimieren*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 2008.
7. Alfadhlani; Samadhi, T.; Ma'ruf, A.; Toha, I. A Framework for the Development of Automatic DFA Method to Minimize the Number of Components and Assembly Reorientations. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *319*, 12083. [CrossRef]
8. Eskilander, S. *Design for Automatic Assembly: A Method for Product Design: DFA2. Dissertation*; Kungliga Tekniska Högskolan: Stockholm, Sweden, 2001.
9. Ezpeleta, I.; Justel, D.; Bereau, U.; Zubelzu, J. DFA-SPDP, a new DFA method to improve the assembly during all the product development phases. *Procedia CIRP* **2019**, *84*, 673–679. [CrossRef]
10. Formentini, G.; Rodríguez, N.; Favi, C. Design for manufacturing and assembly methods in the product development process of mechanical products: A systematic literature review. *Int. J. Adv. Manuf. Technol.* **2022**, *120*, 4307–4334. [CrossRef]
11. Madappilly, P.; Mork, O. Review and modification of DFA2 methodology to support design for automatic assembly (DFAA) in the maritime industry. *Procedia CIRP* **2021**, *100*, 744–749. [CrossRef]
12. Shetty, D.; Ali, A. A new design tool for DFA/DFD based on rating factors. *Assem. Autom.* **2015**, *35*, 348–357. [CrossRef]
13. Trommnau, J. Methodik zur Bewertung und Optimierung der Automatisierungseignung des Zusammenbaus von Bauteilkombinationen mit Forminstabilen Einzelteilen. 2022. Available online: https://elib.uni-stuttgart.de/bitstream/11682/12555/3/2022TrommnauJerome.pdf (accessed on 14 May 2024).
14. Boothroyd, G. Design for assembly—The key to design for manufacture. *Int. J. Adv. Manuf. Technol.* **1987**, *2*, 3–11. [CrossRef]
15. Boothroyd, G.; Dewhurst, P.; Knight, W.A. (Eds.) *Product Design for Manufacture and Assembly*; Dekker: New York, NY, USA, 2002.
16. Miles, B.L. Design for Assembly—A Key Element within Design for Manufacture. Proceedings of the Institution of Mechanical Engineers. *Part D J. Automob. Eng.* **1989**, *203*, 29–38. [CrossRef]
17. Sturges, R.H. A quantification of manual dexterity: The design for an assembly calculator. *Robot. Comput.-Integr. Manuf.* **1989**, *6*, 237–252. [CrossRef]
18. Desai, A.; Mital, A. Facilitating design for assembly through the adoption of a comprehensive design methodology. *Int. J. Ind. Eng. Theory Appl. Pract.* **2010**. [CrossRef]
19. Bauer, W.; Rally, P.; Scholtz, O. Schnelle Ermittlung sinnvoller MRK-Anwendungen. *Z. Für Wirtsch. Fabr.* **2018**, *113*, 554–559. [CrossRef]
20. Weber, M.-A.; Schüth, N.J. Integration der Mensch-Roboter-Kollaboration unter Beachtung technischer und personeller Rahmenbedingungen. In *Frühjahrskongress*; Gesellschaft für Arbeitswissenschaft (GfA): Dortmund/Berlin, Germany, 2020; Available online: https://www.arbeitswissenschaft.net/fileadmin/Downloads/Angebote_und_Produkte/Publikationen/GfA_2020_B-13-5_Weber_Schueth.pdf (accessed on 14 May 2024).
21. Petzoldt, C.; Keiser, D.; Siesenis, H.; Beinke, T.; Freitag, M. Ermittlung und Bewertung von Einsatzpotenzialen der Mensch-Roboter-Kollaboration. *Z. Für Wirtsch. Fabr.* **2021**, *116*, 8–15. [CrossRef]
22. Hees, F.; Müller-Abdelrazeq, S.L.; Langer, T.; Voss, M.; Schmitt, R.; Hüttemann, G. (Eds.) *Projektatlas Kompetenz Montage: Kollaborativ und wandlungsfähig*; RWTH Aachen University Lehrstuhl für Informationsmanagement im Maschinenbau: Aachen, Germany, 2019.
23. Ermer, A.-K.; Seckelmann, T.; Barthelmey, A.; Lemmerz, K.; Glogowski, P.; Kuhlenkötter, B.; Deuse, J. A Quick-Check to Evaluate Assembly Systems' HRI Potential. In *Tagungsband des 4. Kongresses Montage Handhabung Industrieroboter*; Schüppstuhl, T., Tracht, K., Roßmann, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2019; pp. 128–137.

24. Linsinger, M.; Sudhoff, M.; Lemmerz, K.; Glogowski, P.; Kuhlenkötter, B. Task-based Potential Analysis for Human-Robot Collaboration within Assembly Systems. In *Tagungsband des 3. Kongresses Montage Handhabung Industrieroboter*; Schüppstuhl, T., Tracht, K., Franke, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 1–12.
25. Teiwes, J.; Banziger, T.; Kunz, A.; Wegener, K. Identifying the Potential of Human-Robot Collaboration in Automotive Assembly Lines using a Standardised Work Description. In Proceedings of the 2016 22nd International Conference on Automation and Computing (ICAC), Colchester, UK, 7–8 September 2016; IEEE: New York, NY, USA, 2016; pp. 78–83.