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# Capability-based task allocation in human-robot collaboration

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**Abstract**

Close and safe interaction of humans and robots in joint production environments is technically feasible, however should not be implemented as an end in itself but to deliver improvement in any of a production system's target dimensions. Firstly, this paper shows that an essential challenge for system integrators during the design of HRC applications is to identify a suitable distribution of available tasks between a robotic and a human resource. Secondly, it proposes an approach to determine task allocation by considering the actual capabilities of both human and robot in order to improve work quality. It matches those capabilities with given requirements of a certain task in order to identify the maximum congruence as the basis for the allocation decision. The approach is based on a study and subsequent generic description of human and robotic capabilities as well as a heuristic procedure that facilities the decision making process.



*Keywords:*

## 1. Introduction

In the continuous strive for economic efficiency of industrial value adding activities, industrial engineers are constantly challenged to determine and implement the ideal scale, the ideal degree of mechanization and automation as well as the ideal work organization principle for the underlying production processes and systems.

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Whereas manufacturing systems are already mechanically assisted, semi- or even fully automated to a large extent, assembly process areas generally remain permeated of manual operations [1]. The reason for this can be presumed in the fact that in assembly systems variant configuration takes place often and, therefore, work contents vary more frequently – a circumstance in which systems with increased level of traditional automation and the resulting limited flexibility are unsuited [2]. In recent years, robot manufacturers have brought a range of power- and force-limited robots to market. They, through inherent safety measures, are capable of working in the immediate surroundings of humans. At the same time, these robots show a higher degree of flexibility than traditional robots, for example due to more intuitive programming solutions.

This opens up the opportunity to deploy such robots into process areas such as assembly. Here, they serve as assistive machines that carry out certain tasks in close conjunction with their human counterparts and thereby increase or improve e.g. capacity, ergonomics or quality of a process. Hence, through combining strengths of robots such as accuracy and endurance with strengths of humans such as cognition and versatility in a joint environment [3], human-robot collaboration (HRC) emerges.

### 1.1. Study on challenges in implementation of HRC

Despite the availability of suitable technology and thorough application-oriented research, actual industrial applications of human-robot collaborations are still rare to be found [4]. On that account, a study was conducted by the authors to investigate the barriers that impede a stronger prevalence of human-robot applications in industrial environments [5]. Within the study size of 34, robot manufacturers (15) and system integrators (14) have been questioned to Likert-scale their perception of the relevance of in total 17 challenges that could arise during the HRC-implementation process. In addition, five (5) companies using HRC have been interviewed qualitatively to verify the study results and achieve a comprehensive perspective.

Two major topic areas that could be identified as perceived challenges are a) HRC safety assessment aspects as well as b) HRC planning aspects.

Amongst the HRC planning aspects 73% of the participants questioned found *identification of HRC-suitable workstation* and *determination of task allocation between humans and robot* a “very large” or “large” challenge in HRC implementation whereas *work place design for HRC* was rated similarly difficult with 68% of the interviewees considering it a “very large” or “large” challenge. Interestingly, technical challenges such as low flexibility of end-effectors or programming effort for changing tasks were not amongst the highest ranked ones.

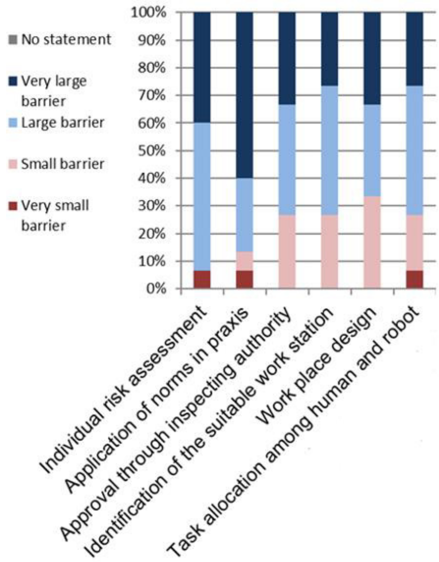


Fig. 1: Top 6 Challenges in implementing HRC [5]

### 1.2. Research focus of this paper

The study results prove that the task of planning a work system that contains human-robot collaboration applications is challenging even for those who are experienced in working with robot technology in an industrial context. To address the identified implementation challenge of *determination of task allocation among human and robot*, this paper is proposing a multi-stage procedure that facilitates distributing available jobs between the two resources human and robot. As the primary decision criterion for the allocation task, *capabilities* were selected to achieve a capability-oriented job assignment.

## 2. State of the art

### *2.1. Human-robot collaboration*

Human-robot collaboration (HRC) is defined as a "state in which a purposely designed robot system and an operator work within a collaborative workspace" [6]. The collaborative workspace is further defined as the "space within the operating space where the robot system (including the workpiece) and a human can perform tasks concurrently during production operation". In practice, HRC describes a situation where humans and mostly articulated robots work jointly on a certain task within a narrow workspace and under absence of safety fences [27].

### *2.2. Function allocation in the context of capabilities*

With the emergence of machines, the traditional assignment of available work to available (human-) resources has been extended by an additional dimension that led to establishing *function allocation* as a subdivision of human factors research. It is supposed to answer the question, which functions should be carried out by humans and which by machines [7], but is not focusing on the task coordination between humans and robots in particular but all kind of machinery that is able to execute mechanic or computational work. Continuing the paradigm of specialization, the focus of optimizing allocation was through suitability – represented by those capabilities required by the task as well as those provided by one of the resources. Initial research in function allocation perceived that, while there are capabilities unique to machines and humans each, there are also overlapping capabilities that provide the opportunity to variably assign tasks (see Fig. 2), e.g. in accordance to resource availability [8]. First systemization of specific capabilities was achieved by Fitts in 1951 who created a list of capabilities to provide a solution for dividing responsibility between men and machines without becoming excessively specific [9].

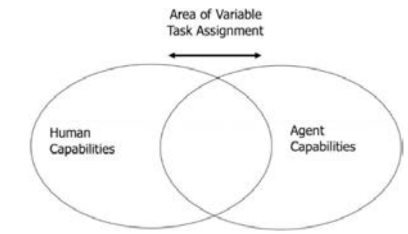


Fig. 2: Adaptive allocation to human and machine [8]

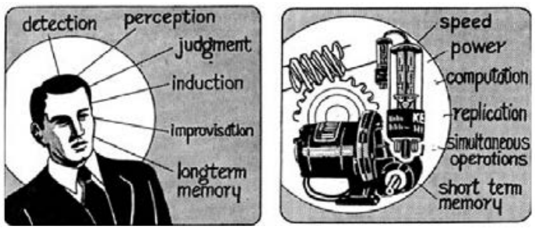


Fig. 3: Illustration of the original Fitts list [9]

In an early reference to function allocation between humans and robots, Nof [10] demands that "emphasis must be placed on optimizing human arousal, job satisfaction and productivity". [11] suggest that arousal and job satisfaction can be penetrated positively through consideration of capabilities, indicating that task allocation in accordance with human and robot capabilities is expedient. In recent years, task planning for human-robot collaboration has been an increasingly popular research scope [28]. [12] introduced the collaboration principles *workplace sharing* and *time sharing* for sequential tasks as they can be found in assembly systems. [13] propose an algorithm for task allocation that minimizes total cost in uncertain environments by comparing different allocation patterns and the probability of the occurrence of change. The task allocation in [14] is based on assessing automation capabilities and assigning only left-over tasks to human operators, so considers machine but not human capabilities for the allocation decision. Such can be supported by checklists that list criteria for automation capacity like [15]. A multi-criterion approach that considers suitability, availability as well as operation time is provided by [16]. These criteria are integrated into a scheduling service, providing ad-hoc task allocation rather than delivering a general, prospective decision. The process-oriented task assignment approach by [4] considers capabilities through a pair-wise comparison of given skills. Another multi-criterion approach, by [18], deliberates determination of a resource's capability into their contribution to corporate goals (quality, time and cost) – assuming that the resource that executes a process at higher quality, in shorter time, at lower cost should have better capabilities. The concept of *capability indicators* is implemented to achieve an objectification of rather fuzzy capability manifestations.

### *2.3. Capabilities for assembly*

Although in 2.2 several task-allocation approaches for HRC could be identified that refer to capabilities, they tend to generalize – robots have certain capabilities, humans have certain capabilities. This can at least be argued since the capabilities of a robot to certain extent depend on its actual equipment whereas capabilities of a human might depend on his actual constitution. A robot equipped with force-torque-sensor, vision system, endlessly rotating wrist joint and an external axis is significantly more capable than one without the before mentioned features, while there are also certain capabilities that cannot easily be enhanced through equipment.

For human operators, a more detailed systemization of its capabilities than the ones identified before is helpful as well. Manual factory work in assembly environments is on the one hand characterized by sensomotoric work that requires coordination of motor skills and the sensor system. This includes, for example, hand-eye coordination, control of applied force, or haptic perception. On the other hand, mental work is required, which contains information reception, processing and decision making [19] [20].

Both categories are not static in their manifestation but subject to progressive change, whereas certain capabilities reduce, approximately from the age of 20 years onwards, and others increase or can at least be maintained through exercise [21]. Prasch found that dexterity, an important capability for assembly tasks, reduces an approximated 30% between age 20 and 60 [22]. Additionally, already in the age-group between 51-55, approximately 13% of operators belong to the group of handicapped staff that is unable to reach the average human performance level in executing physical tasks [23]. The use of HRC implementation based on actual physical and musculoskeletal parameters is proposed by [17].

## 3. Approach for capability-based task allocation in human-robot collaboration

The approach proposed is a three-step procedure enabling a capability-based decision on task allocation. In comparison to existing approaches, this concept differentiates between variably and invariably distributable tasks. Thus, it supports and facilitates an allocation decision also for all tasks that are not critical in terms of the primary allocation target, which in this case is capability-orientation.

First step is detailing the process plan, containing all tasks to be completed and therefor available for task allocation.

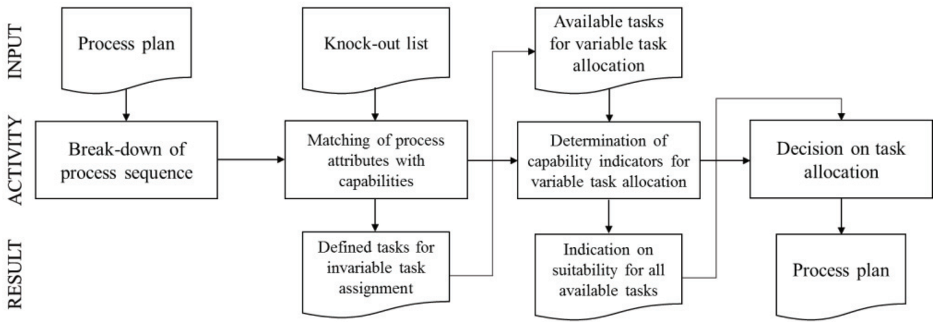


Fig. 4: Staged procedure for capability-based task allocation

### *3.1. Break-down of process sequence*

The break-down of the assembly process delivers the investigation object, in order to carry out the task allocation. This can be both an existing, industrially implemented assembly process that should be enhanced by human-robot collaboration or a future, to-be-implemented process that is supposed to incorporate human-robot interaction right away. Industrial engineering delivers process information on several granularity levels (see Fig. 5). The value stream provides an overview on area level, such as an assembly system. The precedence diagram displays *operations* and their preset sequence that consist of several tasks. Such operation could be “assembly of water pump”. An operation is composed of *tasks* such as “apply bonding material”, “pick and place water pump”, “pick and connect hoses”. On the lowest possible level, a *method time measurement (MTM)* analysis breaks up tasks into elementary motions such as “reach to container”, “grasp water pump”, “move water pump to joining location”, “position water pump” and “release water pump”.

For the further analysis, the *task* level will be used. It is appropriate since a task comprises a complete motion set that requires only one set of capabilities, whereas an operation consisting of several tasks likely requires different sets of capabilities. With the given (un-)flexibility of end-effectors and tooling, probability is high that a specific end-effector is unable to satisfy two largely different sets of required capabilities.

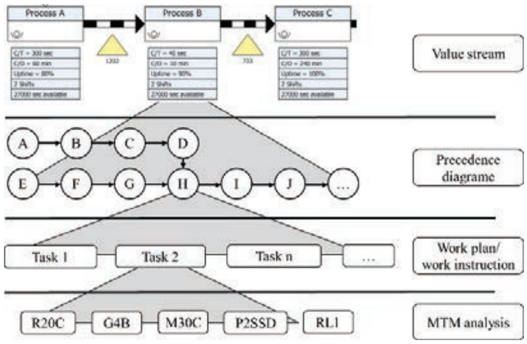


Fig. 5: Levels of process plans in industrial engineering

### 3.2. Invariable task allocation

Following the observation of [8], there might be tasks that are uniquely suitable for humans and others uniquely suitable for machines (robots, in this case). For each of the *tasks* identified through the process sequence break down, it needs to be determined whether they require one of the unique capabilities of humans and therefore cannot be automated or vice versa. For this purpose, a criterion catalogue has been developed from a literature research comprising twelve assembly-relevant human capabilities and ergonomic thresholds. For each criterion, possible characteristics were assigned. Then, for each characteristic, a corresponding task-allocation indication has been assigned. First, the criteria have to be checked on relevance for a specific task. If it is relevant, the true characteristic for the specific task has to be selected.

Table 1: Example from Knock-Out-list for invariable task assignment

| **Assembly task** | **Task-relevant criteria from catalogue** | **True characteristic** | **Task-allocation indication** |
|---|---|---|---|
| Grouting bearing into rear wheel | Applying pressure to object through a wrist joint end position | frequently | robot |
| … | … | … | … |

The resulting indication for the task-allocation decision is displayed to the engineer subsequently. Validation experiments show that in many assembly processes any of the critical criteria from the Knock-Out-list is valid for a certain task – such as simple pick and place processes that require no specific capabilities and strengths. That means, there is no definite indication for the allocation decision and the task has to be considered during the next step to allocate more precise capability indicators. In other cases, more than one criteria might be relevant and the true characteristics might lead to contradicting results. In this case, a tool-deposited weighting will always prioritize ergonomic hazard over capabilities and then make the overall allocation decision in benefit of the robot. Such example is shown in Table 1. Although the task is executable manually, its characteristics will lead to progressive impairment when conducted by human – a knock-out criterion for this approach. In this regard, the human does not have the suiting capabilities for this task and a definite allocation decision irrespective of time, cost or quality can be taken.

Those tasks that are not affected by knock-out criteria can be processed through the variable task allocation procedure.

### 3.3. Variable task allocation

For the variable task allocation, the concept of capability indicators, introduced by [18] will be used. It has been adapted for and validated in powertrain assembly by [25]. The objective here is to objectivize the task allocations decisions in the variable task assignment area as displayed in Fig. 2, where there is no definite answer based on the capability and ergonomics criteria catalogue possible. Therefore, the capability term is deliberated into corporate goals:

- Process time $(p)$
- Additional invest $(i)$
- Process quality $(q)$

The original concept also contains the dimension *work quality*, which in this research has been addressed in 3.2. already as it is the superior objective to be achieved.

Therefore, another catalogue of criteria had to be developed, based on [15,18], containing 25 items that are suitable for assembly of small and compact objects and for related intralogistics processes such as kitting or packaging.

Table 2: Example for criteria for variable task allocation

| **Criteria** | **Characteristic 1** | **Characteristic 2** | **Characteristic 3** |
|---|---|---|---|
| **Type of material provision** | Ordered, orientated | Disordered, varietal purity | Disordered, varietal impurity |
| … | … | … | |

Table 3: Comparative evaluation of resources

| **Capability of resource** | **Cardinal value** |
|---|---|
| Better | 1 |
| Equal | 0.5 |
| Worse | 0 |

For each of those 25 criteria and the corresponding characteristics, a respective capability indicator for both robot and human have to be assigned. For the suitability decision, a better-equal-worse choice is cardinalized (see Table 3). For each of the characteristics, a capability indicator for both human and robot is calculated, as follows, weighting process time, additional invest and quality equally at one third (can be adapted individually):

$$F_h = \frac{p+i+q}{3} \qquad (1) \qquad \text{and} \qquad F_r = 1 - F_h \qquad (2)$$

For a certain assembly task $t$, several criteria $c$ might be relevant and can be weighted again with $w$ again, whereas the sum of all weightings has to equal 1, yielding the capability indicator for the task for each resource:

$$e_{h,t} = \frac{\sum F_{h,c} * w}{\mathrm{c}} \qquad (3) \qquad \text{and} \qquad e_{r,t} = \frac{\sum F_{r,c} * w}{\mathrm{c}} \qquad (4)$$

With capability indicators for each resource and each task included in the variable task allocation procedure, a matrix can be derived and the available tasks be assigned in accordance with the capability indicators. The required information for making the better-equal-worse decision on the process time can be gained through estimation, simulation or predetermined motion time systems such as MTM and RTM (robot time and motion). In an example for 8 assembly tasks, the result of the procedure, including invariable and variable task allocation and using the concepts of pair-wise comparison and capability indicators could be visualized as shown in Fig. 6. The assembly tasks 1, 2, 5 and 6 were allocated as invariable tasks due to their significance regarding unique capabilities, the tasks 3, 4, 7 and 8 were allocated based on quantitative capability indicators taking into account multiple criteria as described above.

$$E = \begin{array}{r c} & \begin{array}{cc}\text{Capability indicator:} \\ \text{Human} \quad \text{Robot}\end{array} \\ \mathit{assembly\ task}\ 1 & \\ \vdots & \begin{pmatrix} e_{h,t} & e_{r,t} \\ \cdots & \cdots \\ e_{h,n} & e_{r,n} \end{pmatrix} \\ \mathit{assembly\ task}\ 8 & \end{array} \qquad (5)$$

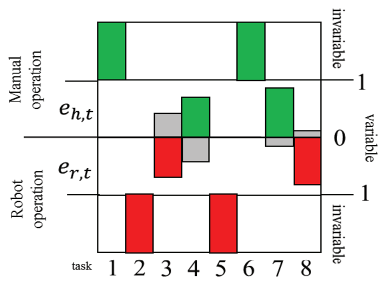

Fig. 6: Visual representation of the allocation results

For an initial validation of the described approach, use case implementation in a Learning Factory was chosen. Learning factory assets are suitable research environments for application-oriented research undertakings as they provide industry-relevant use cases of sufficient extent and avoid the necessity of abstraction, assumption and simulation. Also, they deliver a "try and feel"-experience that goes beyond the pure theoretical validity of the approach results. Furthermore, they allow research outcome to be transferred to education and training immediately.

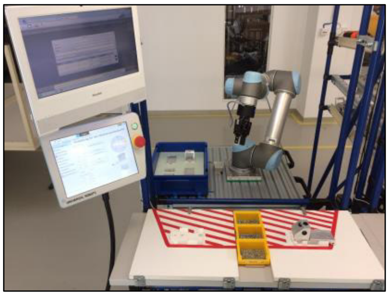

Fig. 7: Assembly use case,
TU Wien Pilotfabrik Industrie 4.0

Fig. 8: Kitting use case,
ESB Logistics Learning Factory

Firstly, a kitting application has been implemented at *ESB Logistics Learning Factory* at Reutlingen University (Fig. 8). While the process itself is rather repetitive and consists of pick-and-place-tasks mostly, parts and components differ widely in terms of their characteristics including dimension, geometry and weight. This helps to understand whether and prove that the approach is able to consider most possible variations of parts and components in the allocation decision. In the *TU Wien Pilotfabrik Industrie 4.0*, a product final assembly process has been realized for validation purposes (Fig. 7). Here, various manipulative skills are required and have to be accounted in the task allocation - including tactile perception, application and regulation of force as well as dexterity.

This combined approach proved to be expedient and fulfills the criteria of a heuristic procedure – structurally analyzing the object of investigation with finite knowledge to achieve a feasible, practicable solution within reasonable time [24]. Still, it has to prove its practicability in industry.

## 4. Conclusion

Firstly, this paper revealed that, although thorough research has been conducted on task allocation in human-robot applications, exactly this design aspect is still one of the major challenges for engineers that impedes further dissemination of the HRC idea. Despite manipulating and safety technology is available manifold, planning and design techniques are lacking. Hence, the further focus for the work could be determined.

For capability-based task allocation, two fundamental approaches could be identified through state-of-the-art research – pair-by-pair comparison of capabilities, delivering a subjective but fast orientation in task allocation as well as the more effortful concept of capability indicators, who achieve a more objective quantification of capabilities through delineating the term *capability* into its influencing dimensions and subsequent aggregation. Under awareness of the fact that there are capabilities that are unique to humans and others that are unique to machines and that these can be identified and described, for a task allocation problem, there is a decision-making arena in which tasks can be assigned with a high degree of certainty and for which the pair-wise comparison is meaningful. Under awareness of the fact that there are also common capabilities which differentiate by nuances only, there is another decision-making arena, where simple, binary decisions on a subjective basis are not expedient and a further deliberation of the problem is helpful.

To achieve the desired capability-based task allocation that supports job satisfaction, considering both sensory and motoric strengths and ergonomic limitations of the human, a two-staged decision making process has been proposed. First, distribution of those tasks that definitely require and support one of the human-unique capabilities and therefore should or cannot be automated *or* have to be automated due to the degree of impairment they may impose the human operator to (under preclusion of other aspects such as cost or time). Secondly, distribution of the remaining tasks which both resources could be suitable for, considering their respective quantified capability under consideration of the constituting elements cost, time and quality.

Still, the approach does not cope with one of the findings from state of the art research: Human capabilities considered for capability-based task allocation are not invariable, but change through age progression, accidents or medical conditions, and in general can be pronounced stronger or weaker individually as well as being enhanced through training and exercise. To be able to consider the individual manifestation of capabilities to achieve a task allocation that suits a particular person instead of humans in general, they need to be assessed and quantified – in order to be processed within the task allocation procedure. Further research will focus on identification and development of techniques to evaluate and quantify human-inherent, manual factory work-relevant prowess such as dexterity or surface sensitivity – to be able to move from capability-based to individual, capacity-based task allocation.

## References

[1] P.R. Spena, P Holzner, E Rauch, R Vidoni, D.T. Matt. Requirements for the Design of flexible and changeable Manufacturing and Assembly Systems: a SME-survey. Procedia CIRP 41 (2016) pp. 207-212.
[2] S. Takata, T. Hirano. Human and robot allocation method for hybrid assembly systems. In: CIRP Annals – Manufacturing Technology 60 (2011), no. 1, pp. 9-12.
[3] G. Michalos, S. Makris, J. Spiliotopoulos, I. Misios, P. Tsarouchi, G. Chryssolouris. ROBO-PARTNER: Seamless Human-Robot Cooperation for Intelligent, Flexible and Safe Operations in the Assembly Factories of the Future. Procedia CIRP 23 (2014) pp. 71-76.
[4] R. Müller, M. Vette, O. Mailahn. Process-oriented task assignment for assembly processes with human-robot interaction. Procedia CIRP 44 (2016) pp. 210-215.
[5] C. Gaede, F. Ranz, W. Echelmeyer, V. Hummel. A Study on Challenges in the Implementation of Human-Robot Collaboration (in publication)
[6] ISO 10218-1:2011, 3.4
[7] Hancock PA, Scallen SF (1996) The future of function allocation. Ergon Des Q Hum Factors Appl 4:24–29
[8] J.M. Bradshaw, M. Johnson, P.J. Feltovich. Human-Agent Interaction. Article, 2011.
[9] P.M. Fitts, ed. Human Engineering for an Effective Air Navigation and Control System. Washington, D.C.: National Research Council, 1951
[10] S.Y. Nof. Handbook of Industrial Robotics. 2nd Edition. ISBN 0-471-17783-0
[11] O. Leßmann, J.M. Bonvin. Job-satisfaction in the broader framework of the capability approach. management revue, 22 (1), pp. 84-99, DOI 10.1688/1861-9908_mrev_2011_01_Lessmann
[12] J. Krüger, T.K. Lien, A. Verl. Cooperation of human and machines in assembly lines. CIRP Annals – Manufacturing Technology 58 (2009), pp. 628-646
[13] S. Takata, T. Hirano. Human and robot allocation method for hybrid assembly systems. CIRP Annals – Manufacturing Technology 60 (2011), pp. 9-12
[14] M. Fechter, P. Foith-Förster, M.S. Pfeiffer, T. Bauernhansl. Procedia CIRP 50 (2016) pp. 629-634
[15] A. Deutschländer: Integrierte rechnerunterstützte Montageplanung München: Hanser, 1989 (Produktionstechnik - Berlin 72). Berlin, Techn. Univ., Inst. für Werkzeugmaschinen und Fertigungstechnik, Diss. 1989
[16] P. Tsarouchi, A.S. Matthaiakis, S. Makris, G. Chryssolouris. On a human-robot collaboration in an assembly cell. International Journal Of Computer Integrated Manufacturing (2016). http://dx.doi.org/10.1080/0951192X.2016.1187297
[17] C. Thomas, L. Stankiewicz, A. Grötsch, S. Wischniewski, J. Deuse, B. Kuhlenkötter. Intuitive work assistance by reciprocal human-robot interaction in the subject area of human-robot collaboration. Procedia CIRP 44 (2016) pp. 275-280
[18] K. Beumelburg. Fähigkeitsorientierte Montageablaufplanung in der direkten Mensch-Roboter-Kooperation. Approved dissertation, Institut für Industrielle Fertigung und Fabrikbetrieb (IFF), University of Stuttgart, 2005.
[19] K. Landau, R. Wimmer, H. Luczak, H.P. Mainzer, G. Winter. Anforderungen an Montagearbeitsplätze. In: K. Landau, H.Luczak (Ed.): Ergonomie und Organisation in der Montage. München: Hanser 2001.
[20] Rohmert, W.: Taschenbuch der Arbeitsgestaltung. Grundlagen und Anwendung arbeitswissenschaftlicher Erkenntnisse. 3. edition. Cologne: Bachem 1980.
[22] J. Täubert, A. Reif. Leitfaden zur alter(n)sgerechten physiologischen Arbeitsgestaltung in der Montage. Chemnitz: 1997. (Wissenschaftliche Schriftenreihe des Instituts für Betriebwissenschaften und Fabriksysteme 14)
[23] M.G. Prasch: Integration leistungsgewandelter Mitarbeiter in die variantenreiche Serienmontage. Lehrstuhl für Werkzeugmaschinen und Fertigungstechnik der Technischen Universität München, approved disseration, 2010.
[24] J.F. Egbers: Identifikation und Adaption von Arbeitsplätzen für leistungsgewandelte Mitarbeiter entlang des Montageplanungsprozesses. Lehrstuhl für Werkzeugmaschinen und Fertigungstechnik der Technischen Universität München, approved disseration, 2013.
[25] G. Gigerenzer, P.M. Todd. Simple heuristics that make us smart. Oxford University Press, New York 1999
[26] D. Schröter, P. Jaschewski, B. Kuhrke, A. Verl. Methodology to identify applications for collaborative robots in powertrain assembly. Procedia CIRP 55 (2016), pp. 12-17
[27] F. Busch, J. Hartung, C. Thomas, S. Wischniewski, J. Deuse, B. Kuhlenkötter. Individualisierte Arbeitsassistenz in der Produktion. Industrie Management (29) 2013, pp. 7-10.
[28] P. Tsarouchi, S. Makris, G. Chryssolouris. Human-robot interaction review and challenges on task planning and programming. International Journal of Computer Integrated Manufacturing. Vol. 29, 2016 – Issue 8, pp. 916-931.