Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-32 (2016) 060–065

Planning Operator Support in Cyber-Physical Assembly Systems

Philipp Hold*,, Fabian Ranz**,***, Wilfried Sihn*,**, Vera Hummel*****

**Technical University Vienna, Institute of Management Science*
Fraunhofer Austria
Austria (philipp.hold@fraunhofer.at)
***Fraunhofer Austria, Vienna*
Austria (fabian.ranz@fraunhofer.at)
*** Technical University Vienna, Institute of Management Science*
Fraunhofer Austria
Austria (wilfried.sihn@fraunhofer.at)
**** ESB Business School, Reutlingen University*
(vera.hummel@reutlingen-university.de)

Abstract: Due to the complexity of assembly processes, a high ratio of tasks is still performed by human workers. Short-cyclically changing work contents due to smaller lot sizes, especially in the varied series assembly, increases both the need for information support as well as the risk of rising physical and psychological stress. The use of technical and digital assistance systems can counter these challenges. Through the integration of information and communication technology as well as collaborative assembly technologies, hybrid cyber-physical assembly systems will emerge. Widely established assembly planning procedures only facilitate the design of purely manual work system. In this paper, two new planning approaches for digital and technical support systems in cyber physical assembly systems will be outlined and discussed with regard to synergies and delimitations of planning perspectives.

Keywords: **Assembly, Complex Systems, Human-Centered Design, Planning, Analyzing, Cognitive Systems, Robotics**

1. CYBER PHYSICAL ASSEMBLY SYTEMS

Assembly systems especially in high-wage countries are faced with the challenge of tackling rising product and process complexity in terms of individualized customer needs and an aging society by demanding preservation of efficiency as well as productivity at the same time. Assembly systems, as they are established in the industry, are reaching their limits increasingly when encountering these challenges. By networking digital data and modern forms of information and communication technology with physical production and assembly processes, altered forms of assembly processes will be possible (Dombrowski et al. (2013)). Assembly processes will be upgraded in this way to adapt economically to requirements of costumer-individual products (Schlund and Gerlach (2013)). Cyber-physical systems (CPS) realize a connection between the physical and the digital world. CPS are composed of a surrounding physical object and an embedded computational system, which collects and processes digital data and interacts with physical processes via actuators. These systems are linked through digital networks and use available data and services globally. CPS are not (technically) closed units. They are defined as open socio-technical systems, which are characterized by a high degree of cross-linking of the physical, social and virtual world as well as by the intelligent use of information and communication systems (Geisberger et al. (2012)). By integrating assembly equipment with CPS-characteristics into assembly environments, so called cyber-physical assembly systems (CPAS) will emerge. Existing examples for such equipment are fastening tools that identify product variants through ICT and parameterize automatically in accordance or small parts containers which are able to determine their fill level and communicate with the parts supplier to assure accurate replenishment.

In addition to cost pressure in global competition and the need for age-appropriate work environments, more frequent changes of work contents as a result of higher product variance, reduced lot sizes and shortened product life-cycles make it more difficult for assembly operators to build-up task routine. In this regard, industrial robots have been used already in the past to automate certain tasks for improved production economy and to relief human workers from rough and strenuous working conditions (Krüger et al. (2009), Drust et al. (2013)). At the same time, information provision was used to deliver operators with instructions and details required to successfully fulfil manually executed tasks, mainly paper based (Wiesbeck (2015)). During recent years, *collaborative robots* have been developed, which, due to their on-board sensitivity as well as communicative and cognitive capabilities, are better than ever able to directly support humans physically in manufacturing processes, as shown in Michalos et al. (2015) and can therefore be called *technical assistance systems*. Simultaneously, latest developments in the field of augmented reality as well as mobile and wearable devices have enhanced possibilities to provide information to operators right on the work process as needed and in a digital format – *digital assistance systems* emerge (Hold et al. (2015)). In this regard, industrial and system engineers are

2405-8963 © 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.12.190

supposed to develop and deploy an appropriate as well as technically feasible degree of operator assistance to achieve a human-oriented, efficient work environment. Therefore, the authors' research reflected by this paper is supposed to identify and develop an integral methodical approach that helps engineers to design CPAS which integrates technical and digital assistance systems. Beyond technical feasibility and temporal aspects of robot use, an important design dimension to be considered is capabilities of humans and robots and actual need for assistance.

2. TECHNICAL ASSISTANCE SYSTEMS

In a simplified perspective, robots for example have advantages in carrying out monotonous, repetitive tasks that require high precision and path accuracy, while human operators are better skilled for tasks which require situative force regulation or vision-hand coordination. Under purposeful consideration of human and robotic skills and strengths, ergonomics can be improved in hybrid over manual work systems. The result is a *hybrid* assembly system (Consiglio et al. (2007), Lotter (2012)).

Human-robot collaboration was standardized most recently by ISO/TS 15066 and can take place within four essential collaboration modes:

- *Safety-rated monitored stop*: Robot stops operation as soon as an operator enters the collaborative workspace.
- *Hand guiding*: Robot motion happens only through direct, manual operator input.
- *Speed and separation monitoring*: Robot decelerates as distance between robot and operator decreases, and comes to complete stop if a minimum distance is fallen short of.
- *Power and force limiting by inherent design or control*: In collision events, robot imparted forces are below threshold values that may cause substantial injury.

For immediate human-robot collaboration in assembly, primarily power and force limited robots are suitable, as only they allow concurrent action of human and robot within narrow work environments and action distances. Fig. 2 shows the overlap of reach and gripping areas of operators and robots in a joint workspace. Such robots are for example equipped with force/torque sensors or they monitor motor currents to detect collisions and stop movements. From a work organizational perspective, integration of robots and humans is conceivable in assembly lines of any shape to single workstations and in parallel as well as face-to-face arrangements.

3. DIGITAL ASSISTANCE SYSTEMS (DAS)

Operators are supported by DAS during the execution of their activities with the aim to minimize or to eliminate the discrepancy between available operators' knowledge and the required knowledge to successfully fulfil a certain assembly task, in order to increase the productivity (Spillner (2015)) through thought-out digital representation of information. The primary objectives of DAS are reduction of training time, search times, operating errors and improving the work force in stressful situations (Zaeh et al. (2007)). The functionalities of modern DAS come far beyond sheer representation of information, but provide a real-time, synchronous, and thus situational support through networking with the assembly periphery (tools, material, work piece, etc.). This means, work instructions are automatically synchronized in accordance with work progress and without any manual interaction with the system. The assembly sequence provides therein the use of the correct work piece, the correct fastening tools, materials etc. - monitored by sensors and cameras. Through logical relations of their signals with corresponding process data, the right work instruction is provided to the operator. In case of assembly mistakes, appropriate software identifies the correct support and generates a specific information in order to have the mistake corrected right in the moment, at the right location to achieve product quality as desired. To be able to define the advantageous components of DAS already within in the planning phase of complex assembly systems, it is necessary to identify the specific DAS needs and to derive the specific requirements for technical components for an adequate provision and also in regard to evaluate the economic and productivity impact of the assistance service system on the entire assembly system.

4. PLANNING AND ANALYZING OF ASSISTANCE FOR CYBER-PHYSICAL ASSEMBLY SYSTEMS

Although hybrid set-ups allow a combination of the flexibility of manual systems with operating cost baseline of automated systems and optimal capability utilization of both human and robotic resources, around 84% of industrial assembly systems in Europe are still dominated by purely manual labour, while only in 12% operators are technically assisted in task execution (Spena et al. (2015)).

The implementation of technical assistance systems requires detailed planning of the proposed process, the required equipment and the evaluation of system design variants with regard to capacity and cost. Thorough research has been conducted on determination of the optimal automation degree (Westkämper (2001), Lotter (2012)), but does not focus on direct interaction of humans and robots. Beumelburg (2005) found that any of the prevalent methods for the design of assembly systems takes it into account at all. According to Lotter (2012), the fundament for the planning and design of a hybrid work process is the manual process.

As for technical assistance systems, methods to determine the necessity of information provision, communication technology requirements in regard of productivity potential in the context of the complexity between human, technology and organization are not mentioned in existing work adequately. The comparison of different variants of assembly process planning approaches demonstrates that planning and analyzing of DAS and their components, especially in regard to answering the question, what impact a DAS will have on the performance of the operator and on the productivity of the assembly system (and of CPAS in particular) is currently one of the key problems (Spillner (2015), Wiesbeck (2015), (Konold and Reger (2013), Lotter (1992), Bullinger (1986)).

The reasons for this are mainly based on the lack of practice proven research findings with regard to relations between the characteristic of assembly tasks, taking into account their complexity and corresponding requirements of DAS (Claeys et al. (2015), Wiesbeck et al. (2015), Reinhard and Spillner (2010)).

Therefore, the authors strive to identify expedient approaches in academia to develop an integrated method that allows design and evaluation of hybrid, cyber-physical work processes. The developed approach for identifying human-robot collaboration opportunities and information necessities looks as follows:

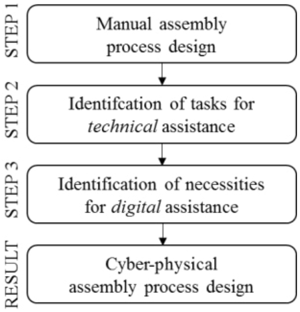


Fig. 1: Approach for design of CPAS

4.1 Step 1: Manual assembly process design

The manual assembly process, characterized primarily by its tasks and their chronological order, is the basis for planning a cyber-physical assembly process. For modelling and describing a manual assembly process, two essential methods can be used: Firstly, the required operations can be visualized through an assembly precedence diagram, outlining all possible assembly sequences of a certain product (see Fig. 2).

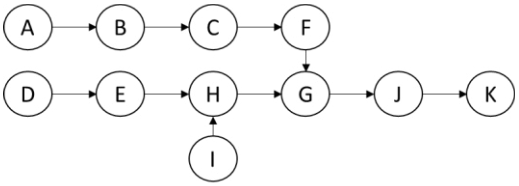


Fig. 2: Exemplary assembly precedence diagram for *K* operations

In a second steps, the actual tasks that are contained in one operation can be described using the Method Time Measurement (MTM) methodology. MTM is a system of predetermined motion systems (Bokranz and Landau (2012)), which allows prediction of process times within a manual work system through the analysis of motion sequences. The time required for the execution of a particular work task is influenced by positioning, orientation and the weight of the provided assembly objects. Results of a MTM analysis are structured movement sequences based on 17 basic motions (e.g. reach, grasp, move, position, release, press, turn, separate, visual functions). Each basic motion is assigned to standard values, which are governed by a uniform, internationally accepted standard of performance and are predetermined in their value through acquired influence factors. MTM is a tool for the description, analysis, planning and design of work systems using standardized process modules. A process element is a sequence section with defined work content (sector neutral) and clear use, for which a time standard applies. The use of MTM provides a valid basis for the evaluation of productivity - taking into account the human capability and supports the identification of deficiencies in (manual) processes (Bokranz and Landau (2012), Maynard et al. (1948)). An exemplary MTM analysis for operation *A* (see Fig. 3) breaks down the process into the mentioned standard motions and assigns a time value based on motion time studies:

Task	Influencing variables	MTM code	Time value (s)
Reach to parts container	Motion length: 40 cm	R40C	0.59
Grasp part from container	Selection of part from mixed pieces container; part size 7x7x4 cm	G4B	0.33
Bring part to fixture	Motion length: 40 cm; Part weight: 0.3 kg	M40C	0.67
Position part in fixture	Symmetrical part; tight fitting - slight pressure required	P2SE	0.71
Release part	-	RL1	0.07
		TOTAL:	2.37 s

Fig. 3: Exemplary MTM analysis for operation A

4.2 Step 2: Identification of tasks for technical assistance

Once the manual assembly process is described with regard to the operations themselves, their precedence and their required motion time, identification of tasks that should be carried out by the assistance system can take place. The key problem in planning of technical assistance is to identify the process tasks that should be taken over entirely or partly by the assistance system. Purpose of Step 2 of the planning approach is specification of the task sharing between humans and robots in cyber-physical assembly systems.

Automation obstructions

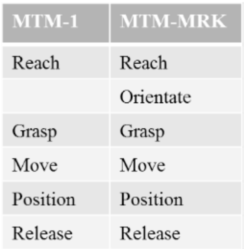
Walther (1985) lists hindrances for automation of an assembly process (see Fig. 4). Those criteria, composed to a checklist, can serve as a first indication for a potential assignment of an assembly operation to the collaborative robot. While being hands on, this approach does not consider human capabilities and their limitations for task assignment, but only generic technical feasibility – without consideration of specific features of certain robotic equipment. Still, the criteria can provide a first impression on viability of human-robot collaboration and the technical effort that can be expected.

Automation obstruction	Op. *A*	…	Op. *K*
Rough part tolerances	Yes		No
Poor accessibility of the joining location	No		No
Limpness of components	Yes		No
High joining forces and torques	No		Yes
…	…		…

Fig. 4: Exemplary automation obstructions

Cycle time-based task sharing

A more quantitative decision basis for task sharing in human robot collaboration is evaluating and optimizing the process from a temporal perspective. In general, cycle times are an important indicator not only in regard of capabilities but for capacity and cost evaluation of processes as well as balancing of resources for optimal capacity utilization. Experimental test set-ups as well as extensive 3D-simulations are usual ways for determining robotic cycle times, but are time consuming, costly and require special competencies. In contrast, Schröter et al. (2016) introduces MTM-MRK which, based on the idea of MTM, breaks down a robotic process into its segments (see Fig. 5) and assigns a respective cycle time.



MTM-1	MTM-MRK
Reach	Reach
	Orientate
Grasp	Grasp
Move	Move
Position	Position
Release	Release

Fig. 5: Motion elements for humans and robots (Schröter et al. (2016))

For each of these standard motions, robot cycle times can be ascertained (calculated). For a simple *Reach* robot motion between two waypoints, cycle time t_c can be described as shown in (Fig. 6), with t_t being the actuation time and t_s the dying out time:

$$t_c = t_t + t_a + t_v + t_d + t_s \tag{1}$$

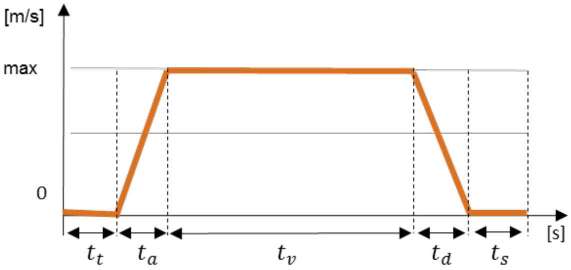


Fig. 6: Cycle time components of a robotic motion (Lotter (1992))

Beyond acceleration/deceleration in mm/s², velocity in mm/s and motion length in mm, type of movement (linear or joint) as well as dead time of the robot control, type of stop at the waypoint (blended or exact) are the relevant time influencing factors (Schröter et al. (2016)).

A time and motion analysis based on MTM-MRK provides a relatively accurate (+/- 3%) cycle time for robot task execution that can either be directly compared to a MTM cycle time from the manual assembly planning section for automation decision, optimizing production through-put time, or just be used as an cycle time indication in early phases of the assembly planning process.

Capability-based task sharing

Beumelburg (2005) extends the pure consideration of circumstances on the process side by matching them with specific capabilities offered by humans and robots respectively through a matrix-based optimization procedure. Initially, automation-relevant criteria and their respective attributes with regard to assembly process, ergonomics, the product itself and material staging are catalogued. For each of those attributes, a specific capability indicator for human and robot is developed, which considers impact of a certain present attribute on

- Execution cycle time
- Required additional invest
- Process reliability and
- Work quality.

Hereby, human and robot are compared on an ordinal basis: better, equal or worse capabilities. The actual (manual) assembly process as designed in Step 1 has to be evaluated with regard to the occurrence of a certain attribute. For each assembly operation, this procedure allows an indication on which resource is rather capable of executing the related process. As a result of several multiplications, weighting and normalization iterations, this method delivers a task and resource specific capability indicator that can be compared to the respective alternative.

$$E = \begin{array}{cc} & \begin{array}{c}\text{Capability indicator:}\\ \begin{array}{cc}\text{Human} & \text{Robot}\end{array}\end{array} \\ \begin{array}{c} \textit{assembly operation A} \\ \vdots \\ \textit{assembly operation K} \end{array} & \begin{pmatrix} e_{iA}^{H} & e_{iA}^{R} \\ \cdots & \cdots \\ e_{iK}^{R} & e_{iK}^{R} \end{pmatrix} \end{array} \tag{2}$$

Therefore, the matrix E allows an optimization of the task-sharing problem based on actual capabilities. The approach of Beumelburg (2005) shows high integrity due to the diverse factors that contribute to the definition of the capability indicators and in combination with the other described methods offers a decision basis for the task sharing problem.

Once tasks out of the manual process spectrum are selected for automation, the remaining manual processes have to be evaluated for potentially necessary digital assistance to further support operators.

4.3 Step 3: Planning and Analysing Digital Assistance Systems

The specific objectives of the model are focused on planning (prospectively) and analyzing (retrospectively) DAS needs in complex assembly systems in CPS environments, while taking into account individual work tasks as well as operators' individual skills, qualifications and performance levels. The model supports the definition of technical and functional requirements for the conception and design of a DAS, concerning quantitative statements with regard to expected productivity effects on the work system. In this way, the model can be used for decision support in regard to an investment project (Output Factor). Therefore, the model is based on the systematic of MTM (Input Factor). Planning and analyzing of digital assistance needs currently encounter methods like MTMs and related ones to their limits, because they do not consider requirements of modern information and communication technologies and also they do not address operator characteristics or performance capabilities sufficiently. The lack of consideration of individual actions of the production worker and the limited knowledge of the production environment (context) make it difficult to plan and to analyse DAS needs adequately in regard to the individual characteristics of the production worker (Zaeh et al. (2007)). Despite the lack of relevant factors, MTM is chosen as input factor for the model, in accordance with the assumption that MTM is applied already in industry and addresses, in addition to the standard time relevant indicators to derive digital assistance needs, such as information of positioning, orientation, weight and length, gripping and also indicators for the human work load (Kuhlang (2015)) Furthermore, the methodology of MTM illustrates an adequate tool for a detailed analysis of work tasks and sequences of varied work tasks.

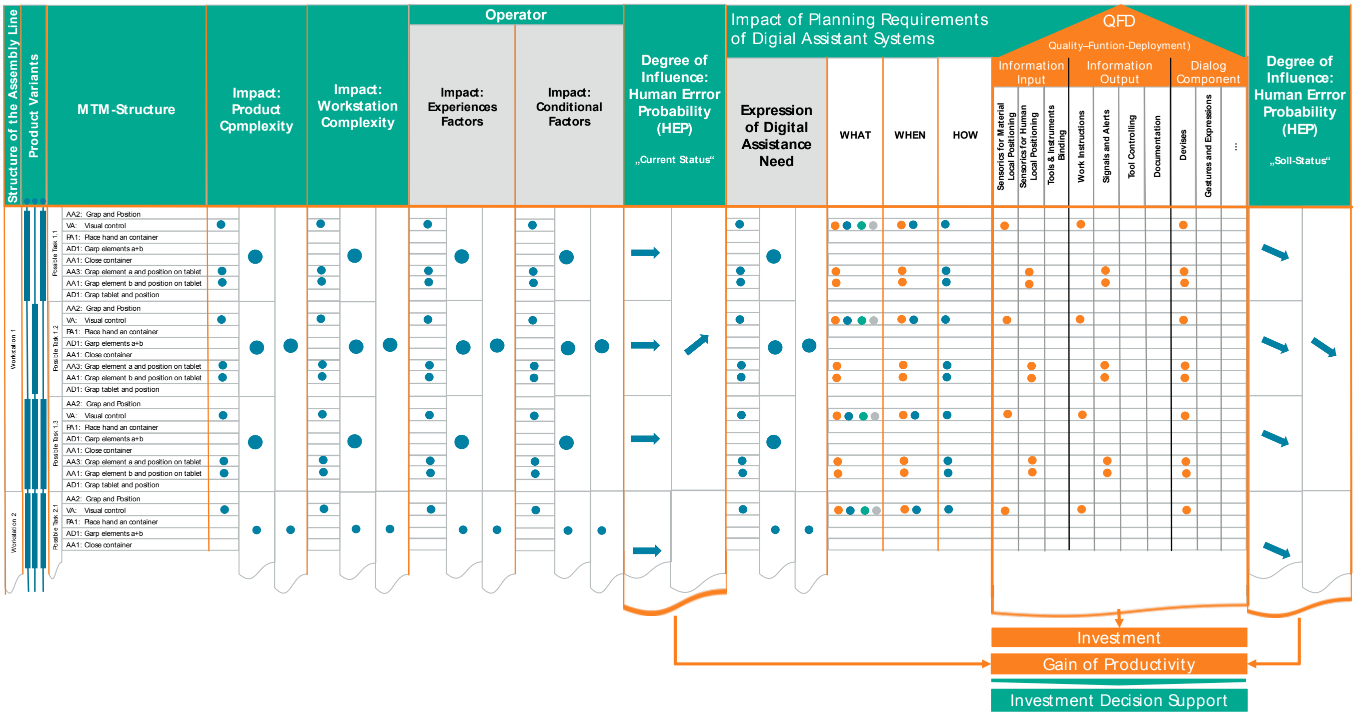


Fig. 7: Schematic structure of the model

The model is based initially on two perspectives of complexity - product complexity and workplace complexity (Claeys et al. (2015), Zhu et al. (2012), Samy and ElMaraghy (2010)). These complexities are calculated qualitatively and quantitatively based on the individual information from the MTM process elements and their description. Thereby, the analysis is carried out focused on the performance of the work task – based on single steps as well as on sequenced steps – workstation specifically and workstation overlapping. The level of expression provides an initialize reference to the need of digital assistance service.

In addition to this "extrinsic requirement consideration", a further analysis of "intrinsic demand consideration" is performed (Claeys et al. (2015), Zeltzer et al. (2012), Abad and Paynabar (2011)). Here, an analysis of the individual MTM process elements and the described methodical execution takes place in terms of experiences of the operators such as skills, knowhow, dexterity, etc. as well as in terms of ergonomic stress situations. In addition to the use of data mining and text mining algorithms, existing ergonomics analysis methods are applied (e.g. EAWS, KIM, etc.) (Richter (2010). Based on single steps as well as on sequenced steps of varied work tasks, an analysis of the probability of human caused failures takes place by applying the method of "Human Error Probability" (Khan et al. (2006)). The connection between the MTM process elements, the probability of human errors is evaluated as a function of time and regarding monetary consequences. In regard to an adequate structuring and correlation analysis of the inspection fields, “Quality Function Deployment” (QFD) can be used. QFD is a method for supporting a customer oriented product development by means of a series of matrices which work similar to the cost-benefit analysis. Based on the general scheme of the "House of Technologies", different innovation and technology decisions can be derived in a holistic way (Spath (2004)). Through an integrated technology database, required components of DAS will be determined in accordance with the identified needs for digital assistant services. Here, it will be derived what kind of digital assistant service (instruction, additional information, etc.), when (on demand of the operator or automatically) and in which form (mobile, semi-mobile and static) is required (Fässberg et al. (2011)). Based on this knowledge, the different features and technical components of DAS will be implemented in the work system. The analysis is performed along the consideration areas of sensor components for information recording (e.g. sensor components for local positioning of tools and human), for information reproduction and utilization (e.g. instruction forms, signals and events, tool control, etc.) and dialogue management (e.g. devices, controlling, etc.). Above, a final analysis of the influence of the identified components on the human error probability and the impact on the temporal activity execution (e.g. search processes) productivity by the use of DAS in the work system are measured.

5. CONCLUSION AND OUTLOOK

Cyber-physical assembly systems allow to benefit from capabilities of humans and machines in joint production environments. While technological progress has made such systems feasible, their design has to take into account actual operational needs and operators' expectations to achieve user acceptance as well as avoid misinvestment into assistance systems which are not actually necessary. So far, supporting tools for design lag behind. The described 3-step method as well as their respective instruments have been assessed in industry projects to identify application potential for technical and digital assistance systems based on an existing, purely manual and un-assisted work process. Since the described approach is based on engineering data such as assembly precedence and MTM information, that is already available in most companies, it is highly applicable and - due to the generality of these methods - not limited to certain sectors. Still, especially for solving the task sharing problem between robots and humans, the available methods do not holistically consider feasibility, temporal and capability-related aspects but focus on one of them - and until now do not include safety aspects from the beginning. For that reason, the authors will continue to work on integration of the methodical aspects into one consistent solution for the design of human-centric cyber-physical work systems.

6. REFERENCES

Abad, A.G., Paynabar, K., Jin, J.J. (2011). Modeling and analysis of operator effects on process quality and thoughput in mixed model assembly systems. Journal of manufacturing science and engineering, 133 (2), 2011

Beumelburg, K. (2005). Fähigkeitsorientierte Montageablaufplanung in der direkten Mensch-Roboter-Kooperation. ISBN 3-936947-52-X. Jost Jetter Verlag, Heimsheim, 2005

Bokranz, R., Landau, K. (2012). Handbuch Industrial Engineering: Produktivitätsmanagement mit MTM. Schäfer-Peschel, 2012

Bullinger, H. J. (1986). Systematische Montageplanung. Handbuch für die Praxis. München, Hanser, 1986

Claeys, A., Hoedt, S., Soete, N. , Landeghem, H. Van, Cottyn, J. (2015). Framework for Evaluating Cognitive Support in Mixed Model Assembly Systems. IFAC-Pap., Bd. 48, Nr. 3, S. 924–929, 2015

Consiglio, S., Seliger, G., Weinert, N. (2007). Development of Hybrid Assembly Workplaces. *Annals of the CIRP Vol. 56/1/2007*. pp. 37-40, 2007

Dombrowski, U., Wagner, T., Riechel C. (2013). Concept for a Cyber Physical Assembly System. In: IEEE ¬ International Symposium on Assembly and Manufacturing (ISAM), 2013, S. 293-296

M. Drust, T. Dietz, A. Pott, and A. Verl, "Production assistants: The rob@work family," in *Robotics (ISR), 2013 44th International Symposium on Robotics*, pp. 1–6, 2013

Erol, S., Jäger, A., Hold, P., Ott, K. (2016). Tangible Industry 4.0: A scenario-based learning factory approach for future production. Procedia CIRP (Paper acecpted), 2016

Fässberg, T., Fasth, Å., Mattsson, S., and Stahre, J. (2011). Cognitive automation in assembly systems for mass customization. In Proceedings of the 4th Swedish Production Symposium (SPS), Lund, Sweden.

Geisberger, E., Broy, M., Cengarle, M. V., Keil, P., Niehaus, J., Thiel, C., Thönnißen-Fries, H. (2012). agendaCPS. Integrierte Forschungsagenda Cyber-Physical Systems. Hg. v. Eva Geisberger und Manfred Hans Bertold Broy. acatech - Deutsche Akademie der Technikwissenschaften. München, Berlin (acatech Studie). 2012

Hold, P., Ranz, F., Hummel, V., Sihn, W. (2015).

Hummel, V., Hyra, K., Ranz, F., Schuhmacher, J. (2015). Competence development for the holistic design of collaborative work systems in the Logistics Learning Factory. Procedia CIRP 32 (2015), pp. 76-81

Khan, F. I., Amyotte, P. R., DiMattia, D. G. (2006). HEPI: A new tool for human error probability calculation for offshore operation. Saf. Sci., 44/4, pp. 313–334, 2006

Konold, P., Reger, H. (2003). Praxis der Montagetechnik. Produktdesign, Planung, Systemgestaltung. 2. Aufl. Wiesbaden: Vieweg. 2003

Lotter, E. (2012). Hybride Montagesysteme. In: Lotter, B., Wiendahl, H.-P. (Ed.): Montage in der industriellen Produktion – Ein Handbuch für die Praxis. Springer-Verlag Berlin Heidelberg, pp. 167-193, 2012.

J. Krüger, T. K. Lien, and A. Verl, "Cooperation of human and machines in assembly lines," in *CIRP Annals 2009*, pp. 628–646.

Kuhlang, P. (2015). Modellierung menschlicher Arbeit im Industrial Engineering. Grundlagen, Praxiserfahrungen und Perspektiven, Ergonomia Verlag Stuttgart, 2015

Lotter, B. (1992). Wirtschaftliche Montage. Ein Handbuch für Elektrogerätebau und Feinwerktechnik. Düsseldorf: VDI-Verlag 1992

Maynard, H.B., Stegemerten, G.J., Schwab, J.L. (1948). Methods-time Measurement, McGraw Hill, New York.

Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D., Chryssolouris, G. (2015). Design considerations for safe human-robot collaborative workplaces. Procedia CIRP 37 (2015), pp. 248–253.

Reinhart, G., Spillner, R. (2010). Assistenzroboter in der Produktion. In: Intelligente Mechatronische Systeme. Tagungsband. Winterthur 3.-4. November 2010. Internationales Forum Mechatronik. Winterthur: IMS Institut für Mechatronische Systeme, 2010

Richter, G. (2010). Toolbox Version 1.2 - Instrumente zur Erfassung psychischer Belastungen. Dortmund: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2010

Samy, S., ElMaraghy, H. (2010). A model for measuring products assembly complexity. International Journal of Computer Integrated Manufacturing, 23 (11), S. 1015–1027, 2010

Schlund, C. M., Gerlach, S.: Der Mensch im industriellen Holozän. In: Erconomic Egineering, p. 22-26, 2013

Schröter, D., Kuhlang, P., Finsterbusch, T., Kuhrke, B., Verl, A (2016). Introducing process building blocks for designing human robot interaction work systems and calculating accurate cycle times. In Procedia CIRP 44 (2016), pp. 216-221.

Spath, D. (2004). Forschungs- und Technologiemanagement. Potenziale nutzen - Zukunft gestalten. München, Hanser, 2004

Spena,, P.R., Holzner, P., Rauch, E., Vidoni, R., Matt, D.T. (2016). Requirements for the Design of flexible and changeable Manufacturing and Assembly Systems: a SME-survey. Procedia CIRP 41 (2016) pp. 207-212.

Spillner, R. (2015). Einsatz und Planung von Roboterassistenz zur Berücksichtigung von Leistungswandlungen in der Produktion. Dissertation. Herbert Utz Verlag. München. 2015

Walther, J. (19: Montage großvolumiger Produkte mit Industrierobotern (IPA-IAO Forschung und Praxis 88). Stuttgart, Univ., Fak. Fertigungstechnik, Inst. für Industrielle Fertigung und Fabrikbetrieb, Diss. 1985

Westkämper, E. (2001). Modulare Produkte - Modulare Montage. In: Wt Werkstattstechnik 91 (2001), Nr. 8, pp. 479-482.

Wiesbeck, M. (2015). Struktur zur Repräsentation von Montagesequenzen für die situationsorientierte Werkerführung, Dissertation. Herbert Utz Verlag, München, 2015

Zaeh, M. F., Wiesbeck, M., Engstler, F., Friesdorf, F., Schubö, A., Stork, S., Bannat, A., Wallhoff, F. (2007): Kognitive Arbeitssysteme in der Montage. Adaptive Montageführung mittels zustandsbasierter, umgebungsabhängiger Anweisungsgenerierung. In: ZWF - Zeitschrift für wirtschaftlichen Fabrikbetrieb. 2007. pp. 644-650

Zeltzer, L., Limère, V., Aghezzaf, E. H. (2012). Measureing the objective complexity of assembly workstations. In: ICCGI, 2012, The seventh International Multi-Conference on Computing in the Global Information technology, pp. 341-346, 2012

Zhu, X., Hu, S.J., Koren, Y., Marin, S.P. (2008). Modeling of manufacturing complexity in mixed-model assembly lines. Journal of Manufacturing Science and Engineering, 130(5), 2008