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Digital assistance for aircraft manufacturing – process requirements and technologies

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Abstract

High quality and productivity requirements prevail in aircraft manufacturing. To ensure these standards are met, production processes are largely automated and digitalized. However, high product complexity leads to many manual processes which are much more prone to errors and insufficient productivity. To support workers effectively, this paper proposes a concept for workers in aircraft manufacturing, which connects different Digital Assistance Technologies using a Digital Twin. The concept results from the analysis of influencing factors in manual work processes, the investigation of workers in the production environment and a survey on the technology acceptance of different Digital Assistance Technologies.

Keywords: Digital Twin; Operator 4.0; Digital Assistance; IIoT; CPS

1. Introduction

1.1. Motivation

Aircraft production is characterized by highly complex products which, despite the progress of automation, still require a high proportion of manual processes, particularly in fuselage assembly. On average, more than 230,000 drill holes for fasteners and rivets have to be made for each medium-sized aircraft [1]. Of these, around two thirds are produced using manual processes including preparatory and follow-up steps. Drilled holes and rivets must meet precise process parameters such as diameter, torque or drilling angle. High repetition frequencies and varying parameters lead to problems of compliance with these quality requirements. Fuselage assembly is characterized by a particularly low level of automation because the assembly places are often difficult to access [2].

In addition to the qualitative problems of the drilling and riveting processes in aircraft production, the preparatory and follow-up processes are also characterized by a number of problems. Information is provided via a number of cross-referenced documents with a high degree of complexity, resulting in an inefficient search for information and potential errors in the setting of process parameters. Documentation of work progress and quality is mostly done on paper and communicated at shift handover. Consequently, the estimated share of value creation is only about one third of the paid working time [3]. The target variables to be optimized in manual processes in aircraft production are therefore quality and productivity.

A variety of Digital Assistance Systems (DAS) have already been developed to support manual assembly and improve these targets [4]. They are largely limited to the use of one particular Digital Assistance Technology (DAT) for a specific application. In [3] we developed a first DAS for aircraft manufacturing, combining the use of smart tools and tablets in a digital twin (DT) platform. The position of the smart tools is detected using ultrasound. Required parameters such as the torque or the drilling diameter can be determined and transferred to the tool by mapping the position to the CAD system. The platform is leveraged to control and document the parameters by linking the DATs with software services. The aim of this paper is to substantiate the proposed DAS and to investigate which further technologies should be integrated on the scalable platform. The DAS should improve the target factors quality and productivity and link various DATs via a DT. The intention is to create a human-centric cyber-physical system which ensures both the effectiveness of the system and the acceptance of the users while being flexible and scalable in the industrial context.

1.2. Structure and approach

In order to meet the described requirements above, we first determined influencing factors of the manual work process of fuselage assembly. This refers to finding the relevant elements that influence the worker in the execution of the work with regard to quality and productivity. On the one hand, the theoretical effect of these elements on the target variables is to be investigated. On the other hand, the perceived need for support of the workers is to be evaluated in order to obtain a theoretically and practically valid solution. By linking these influencing factors with DATs, a first selection for the DAS will be made. In order to achieve high levels of acceptance by the workers, the final technology selection will be based on an employee survey on perceived usefulness and ease of use.

This paper is structured in six sections. After this introduction we summarize the current state of research briefly in section 2 and scrutinize the process requirements in aircraft manufacturing in section 3 to obtain and analyze the influencing factors. Section 4 evaluates the technology acceptance of workers in aircraft manufacturing and section 5 presents the final selection of DATs for the DAS in aircraft manufacturing. We close the paper with a summary and outlook in section 6.

2. Current state of research

2.1. Definitions

Digital Twins are often defined in different ways in literature. We understand a DT as a combination of physical and tsdigital object, which are integrated using bi-directional data flows [5]. A change in the state of the digital side leads to the same change in the physical objects and vice versa. Physical and virtual objects are connected with the DT data and can be controlled via services [6]. The DT can be understood as core element of the DAS in this paper.

A *Digital Assistance System* integrates various *Digital Assistance Technologies* to support the operators in their work. It combines the use of hardware such a tables or smart tools with software services.

2.2. Quality and productivity

Although there is a separate production management field for each of the target variables quality and productivity, in practice it is often the case that improvement measures cannot be implemented effectively [7]. In order to implement targeted improvements via the DAS, it should be aligned with the operationalized cause-effect relationships of the target variables.

Quality in the context of assembly processes is to be understood as the ratio of the sum of scrap and rework and the achieved yield of good parts [8]. Thus, to improve them effectively, the effects of process capability on the generation of scrap and rework must be considered, as described in [9]. The cause categories known from an Ishikawa diagram and their effect on the mean value and scattering have a direct effect on the process capability and are further operationalized by [9] into 16 actuating variables like information handling, material handling, work equipment or disturbance prevention. These variables can be used to estimate the quality impact by influential factors in manual processes (see section 3).

Productivity for manual processes is defined as the ratio of produced good parts to paid labor hours (or input to output of the labor force) [7]. Thus, to increase productivity, paid absence time and attendance time must be considered. Attendance time in particular can be divided into task-related and non-task-related activities [10]. Figure 1 illustrates the cause-effect relationship between actuating variables and productivity of the workforce, limited to the attendance time. DATs can support the task-related variables defined by [11] in particular, which can be seen highlighted by a blue background as generic work cycle in the illustration. The resulting 12 actuating variables of paid labor hours are used to estimate the productivity impact by influential factors in section 3.

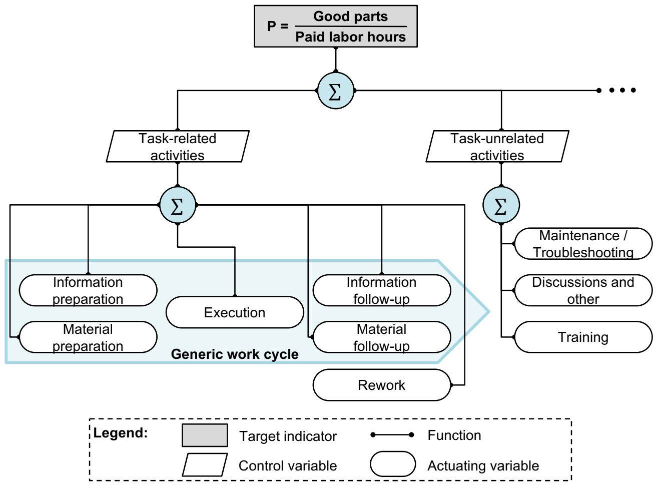

Fig. 1. Productivity control model based on [10] and [11]

2.3. Digital assistance systems and technologies

DAS combine hardware and software components, to supply workers with cognitive and physical support in task-related activities [12, 13]. Assistance functionalities mostly focus on visualizing information to support preparation activities like gathering information or making task-related decisions [14]. Other systems also support the documentation of information through bi-directional data transmission [15] or are used for collaborative work, e.g. in disruption management of one-off production [16].

In aircraft production, there is a growing focus on DAS that also provide physical support. In [17] various DATs are investigated that are intended to support workers during work steps that are ergonomically compromising. These include the use of exoskeletons or collaboration with robotic systems. In [2] and [3] smart tools are integrated in a DAS to support highly repetitive drilling and riveting operations. Nevertheless, the concepts examined are usually designed for a specific area of application.

To provide extensive support for workers in aircraft manufacturing across the generic work cycle and for a multitude of application areas a more comprehensive DAS is needed. This requires a broad analysis of different areas of operation and their respective requirements.

From this, a concept should be derived that links various DATs with each other. Corresponding to the generic work cycle, DATs can provide information, control and document execution, or acquire and interpret data about the environment or product. Information can be provided by technologies such as tablets, smart glasses or projection. Execution can be controlled with smart tools or production means as well as technologies like exoskeletons or smart measuring devices. Data about the environment or the product can be acquired by the use of different sensors or technologies like industrial image processing. DATs from these three areas should be investigated and potentially integrated in a DAS. In order for the resulting DAS to be flexible, it should be based on a DT platform that connects multiple physical objects with digital models via modular interfaces and intervene in the real process using programmable services. In this way, a DAS improving the target variables, the benefit of workers and multiple application areas can be realized.

3. Process requirements in aircraft manufacturing

Process requirements in aircraft manufacturing derive from the task-related activities that structural mechanics have to perform on a regular basis. These activities are subject to various influencing factors that affect the target variables quality and productivity and can be divided into different domains.

To cover both the requirements from theory and practice, a thorough analysis of process documentation and work documents was initially carried out. Then, various workers were observed over several days. In interviews, we asked about problems occurring in different assembly processes. From this, standard activities were defined as well as classified in the generic work cycle and their influencing factors were derived. In the course of a workshop with workers from six different production areas of a large aircraft manufacturer, the standard activities and influencing factors were evaluated and extended when necessary. The influencing factors were examined with regard to their perceived need for assistance (NFA). For this purpose, on the one hand a questionnaire was used to evaluate each factor and on the other hand each worker specified the subjectively three most relevant factors by placing tags on a whiteboard.

3.1. Tasks of assembly workers

Typically, manual assembly processes in aircraft manufacturing can be described as joining two structural components of relatively large size. In addition to informational preparation, the components must first be aligned and fixed to each other using production means. Then the predrilled holes are transferred from one component to the next at the joining points. The holes are brought to their final diameters through several drilling steps. After being drilled, the parts are taken out of position in order to remove chips, which can obstruct the transfer of mechanical forces. After repositioning the components, fasteners are inserted and either tightened to a specific torque or riveted by shear-off collars. In addition to these repetitive assembly steps, pre- and post-assembly activities such as measuring and documenting the quality of execution or applying sealants and conductive materials must be performed. Figure 2 shows an overview of the tasks in the generic work cycle.

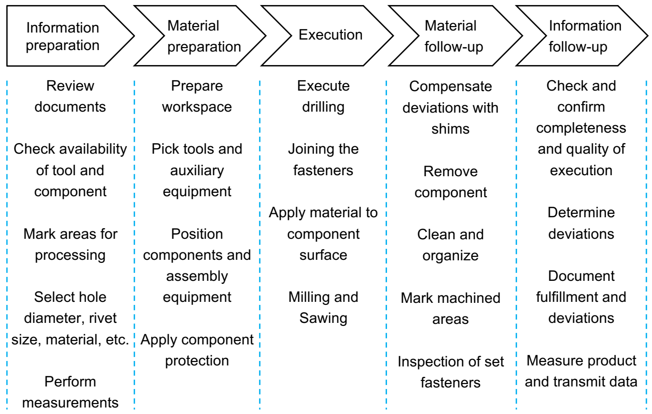

Fig. 2. Tasks of structural mechanics in aircraft assembly

3.2. Influential factors - Worker model

The chosen domains for influential factors are: *information / documents*, *tools / production means*, *process*, *product* and *environment*. These domains correspond to the elements workers interact with in the assembly process. Figure 3 shows the resulting worker model including the domains and their 35 influential factors.

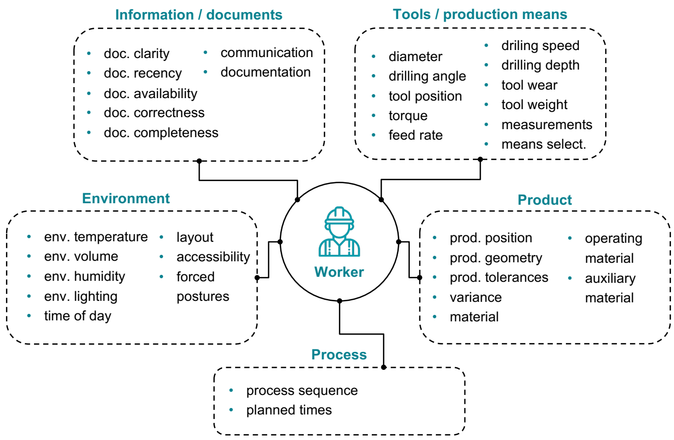

Fig. 3. Worker model of influential factors in aircraft assembly

3.3. Evaluation and rating of influential factors

In order to rate the influencing factors regarding their importance of support by DATs, the respective influence on the actuating variables of quality and productivity was examined.

Subsequently, the evaluated results on the perceived NFA were merged with this study to obtain a prioritization of the influencing factors. NFA was evaluated on a Likert scale from 1 (little support needed) to 7 (assistance is essential) and by the number of tags placed on a factor. Impact on quality and productivity should be understood as number of actuating variables affected.

The overall support rating of a factor is composed from four components (see table 1):

1. Mean value of NFA (Likert-score)
2. Number of tags for subjectively most important factors
3. Number of actuating variables affected in the productivity control model
4. Number of actuating variables affected in the quality control model

For the mean value of the NFA (*1*) and the number of set tags (*2*), a combined rating is generated. Any factor with either a mean NFA of at least 5.5 or at least 2 tags receives an A-rating, any factor with a mean NFA of 5.0 or more or 1 tag receives a B-rating, and all others receive a C-rating. For both the productivity impact (*3*) and the quality impact (*4*), an individual rating is generated each. In the case of productivity impact an A-rating was assigned when 3 or more actuating variables are affected, a B-rating was assigned when 2 variables are affected and factors affecting only 1 variable were rated C. Similarly, quality impact was rated A when affecting 2 variables, B when affecting 1 variable and C when affecting no actuating variables at all.

The final support rating (*5*) was derived by combining the ratings from the three resulting categories. If at least two of the three categories are assigned an A-rating, the factor received the overall support rating A. If all categories have a rating of B or if an A-rating was assigned once, the factor received the overall support rating B. All results below this received the overall support rating C.

Table 1. Rating of influential factors for support through digital assistance

Influential factor	*(1)* Mean NFA	*(2)* # of tags	*(3)* Produc. impact	*(4)* Quality impact	*(5)* **Support rating**
[***tools / means***]					
diameter	5.2	3	4	1	**A**
drilling angle	5.8	-	4	1	**A**
tool position	5.3	1	4	1	**B**
torque	4.8	1	4	1	**B**
drilling speed	5.0	1	4	1	**B**
drilling depth	4.7	-	4	1	**B**
feed rate	4.5	-	4	1	**B**
tool wear	5.8	4	3	2	**A**
tool weight	5.5	3	5	1	**A**
measurements	4.8	1	3	1	**B**
means selection	5.3	-	2	1	**B**
[***information***]					
doc. clarity	4.8	-	3	1	**B**
doc. completeness	4.7	-	3	1	**B**
doc. correctness	4.7	-	3	1	**B**
doc. recency	4.7	-	3	1	**B**
doc. availability	4.3	-	3	1	**B**
documentation	4.8	-	2	1	**C**
communication	5.2	-	3	1	**B**
[***product***]					
prod. position	5.5	-	3	2	**A**
prod. geometry	5.2	-	3	2	**A**
prod. tolerances	4.8	-	3	2	**B**
operating mater.	4.3	-	3	1	**B**
auxiliary mater.	4.2	-	3	1	**B**
variance	5.3	-	3	1	**B**
material	4.7	-	3	1	**B**
[***process***]					
proc. sequence	4.0	-	1	1	**C**
planned times	5.5	2	3	1	**A**
[***environment***]					
accessibility	5.0	-	2	2	**B**
forced postures	5.3	1	2	2	**B**
layout	4.8	-	2	2	**B**
env. temperature	5.7	-	2	1	**B**
env. volume	5.2	-	2	1	**B**
env. humidity	4.7	-	2	1	**C**
env. lighting	5.3	-	2	1	**B**
time of day	4.3	-	2	1	**C**

4. Technology acceptance in aircraft manufacturing

To find out which technologies are well-accepted by workers in aircraft production, the Technology Acceptance Model by [18] was used. The cognitive response on each technology is determined by investigating and scoring the perceived usefulness and perceived ease of use and deriving an overall score.

4.1. Survey explanation

The survey introduced workers to 11 different DATs, in each case describing a potential use case in everyday work. The selection consisted of four technologies for information provision (*tablets/cell phones, smart watches, smart glasses, projection*), three technologies to support execution and documentation (*smart tools, smart measuring devices, exoskeletons*), and four technologies for data acquisition and interpretation (*environment sensor technology, industrial image processing, motion tracking, eye tracking*).

Five statements were made for each technology (see table 2), and the respondents evaluated their level of agreement with them on a Likert scale from 1 (total disagreement) to 7 (total agreement).

Table 2. Statements for technology acceptance

Nr.	Statement	Type
1.	I would like to work with **X**.	Overall
2.	I think using **X** would simplify my work day.	Usefulness
3.	I think the quality of work would improve using **X**.	Usefulness
4.	It would be easy for me to get used to **X**.	Ease of use
5.	I imagine the use of **X** to be clear and understandable.	Ease of use

From the answers, an overall score and a respective score for ease of use and usefulness per technology was derived. To obtain results that are as general as possible, employees from various departments of a large aircraft manufacturer and an original equipment manufacturer were surveyed online. At the time of submission, **26** workers from **8** different departments participated in the ongoing survey. The results were related to the maximum value of 7.

4.2. Survey results

Figure 4 shows the results of the survey. Technologies for data acquisition and interpretation are well-accepted when it comes to data about the product or the environment, but less accepted when acquiring data about the workers themselves. Technologies to support execution and its automatic documentation have a high degree of acceptance for tool operations and measuring values. Acceptance of exoskeletons is low, which may be due to the low rating in ease of use for the difficult-to-access work areas. Information provision seems to be highly accepted when offering to project data on the product or showing data on devices like tablets or cell phones. The use of smart glasses and watches seems to meet a lower degree of acceptance, as the perceived usefulness for smart watches and the perceived ease of use for smart glasses receives a low rating.

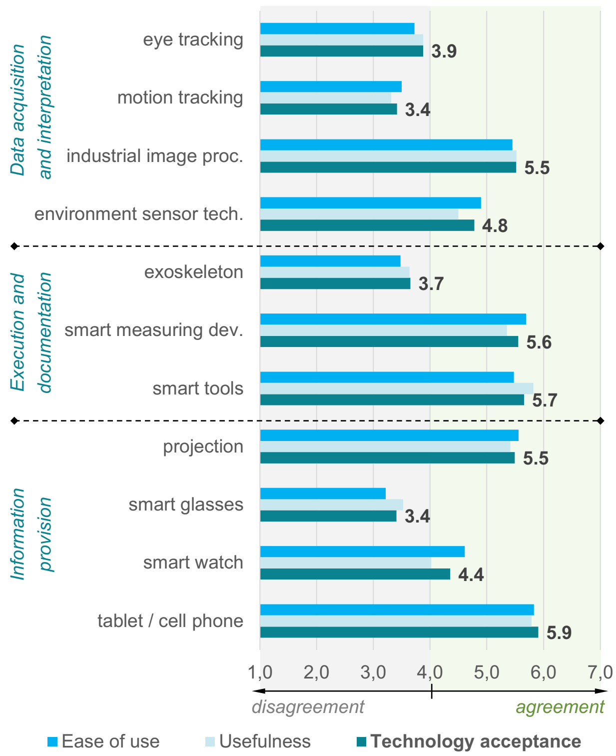

Fig. 4. Technology acceptance scores of surveyed technologies

5. Digital assistance system for aircraft manufacturing

In order to combine the rating of the influencing factors and the acceptance of the assistance technologies into a DAS, it must be examined to what extent the technologies control or improve the influencing factors. From the prioritization of both elements, a proposal for an initial concept can be given, which can subsequently be expanded. Table 3 summarizes the impact of the surveyed technologies on the rated influencing factors from table 1. Influence on an A-rated factor is counted three times, influence on a B-rated factor is counted twice, and influence on a C-rated factor is counted once to account for support relevance. Influencing all 35 factors would lead to a maximum impact of 73.

Table 3. Technology impact for manual assembly in aircraft manufacturing

Technology	A-Factors *(3 points)*	B-Factors *(2 points)*	C-Factors *(1 point)*	**Impact** *(max: 73)*
tablet / cell phone	2	9	2	**26**
smart glasses	2	9	0	**24**
smart watch	0	7	0	**14**
projection	2	7	0	**20**
smart tools	3	9	2	**29**
smart measuring dev.	2	3	1	**13**
exoskeleton	2	4	1	**15**
environment sensor tech.	0	3	3	**9**
industrial image proc.	2	2	1	**11**
motion tracking	0	3	0	**6**
eye tracking	0	4	1	**9**

5.1. Digital assistance system and technology guidelines

Figure 5 visualizes the impact of each technology in relation to its overall technology acceptance score and clusters them in four distinct quadrants separated at an impact score of 12.5 and a technology acceptance score of 5.25.

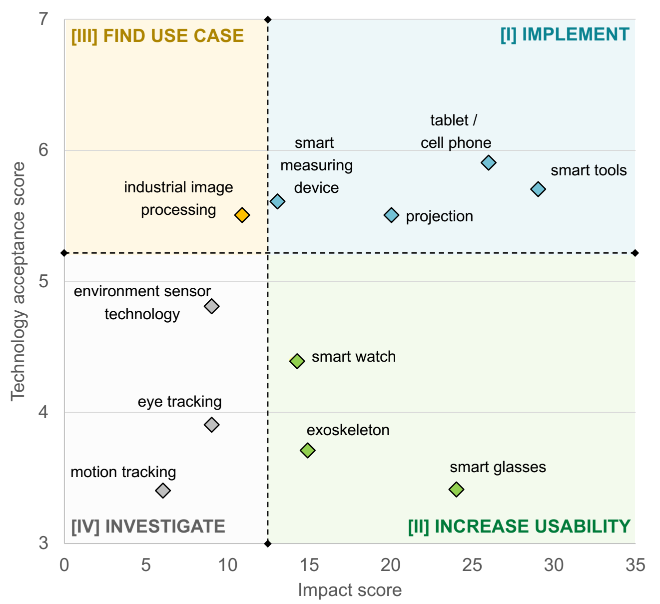

Fig. 5. Impact-acceptance matrix for implementing Digital Assistance Technologies in manual aircraft assembly

Quadrant I contains DATs that have a high impact on influential factors and high acceptance by workers. A first proposal for a DAS in aircraft manufacturing comprises the integration of *smart tools* and *smart measuring devices* for execution and documentation support as well as *tablets* and *projection technology* to provide information about the work plan and product. Technologies in the other quadrants should not be implemented without further investigation.

The DATs from quadrant II should be investigated for possible usability improvements, as they could have a high impact but do not achieve sufficient acceptance among workers. If DATs are in quadrant III, they are accepted by workers but achieve lower values in impact. The development of new use cases should be investigated to determine which other manual assembly tasks (table 2) can be supported in order to increase the influence on the related influential factors (table 1). Remaining DATs in quadrant IV have low acceptance and low impact and should not be integrated.

However, for all DATs it is important to consider exactly which factors are influenced and how important they are for the individual application. Further, it should be considered what the overall impact of the integrated DAS looks like and whether, for example, the integration of environmental sensors covers factors that would otherwise be missed. In all considerations, the implementation effort should be regarded as a third dimension. The proposed DAS covers 23 influential factors (65,7%) and reaches an impact score of 49 (68,1%).

6. Summary and outlook

An in-depth analysis of the requirements for DAS in aircraft manufacturing was carried out. Factors that influence the worker in the manual process were systematically defined. Together with workers, these were evaluated in terms of their support requirements and ranked. Subsequently, various DATs were evaluated in terms of their effect on these factors and examined for acceptance of use via a broad survey. From both perspectives, a classification of technologies could be made, from which an DAS for the worker in aircraft manufacturing was derived and suggestions for action for the integration of further technologies were given.

Limitations of the research are that the evaluation of the quality and productivity impact of individual influential factors and thus of the respective technologies was carried out purely via the quantity of influenced variables of the operationalized target variables. Likewise, the influences of the DATs on the individual factors were hypothesized. An actual assessment depends on the respective application. These points could be deepened in future research. Nevertheless, a concept has been developed which is useful for research and industry and which provides a well founded direction for action. The proposal and the data collected can be used to drive forward digitization in aircraft manufacturing.

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References

[1] Airbus Group, 2015. Qualität - Besser Bohren, in: *Airbus News For Airbus People*

[2] Hintze, W., Lödding, H., Friedewald, A., Mehnen, J., Romanenko, D., Moeller, C., Brillinger, C., Sikorra, J.N., 2019. Digital Assistance Systems for Smart Drilling Units in Aircraft Structural Assembly, in: *International Workshop on Aircraft System Technologies*, Hamburg, Germany

[3] Piontek, S., Lödding, H., 2022. User-Centric Digital Assistance with Smart Tools for Manual Assembly Processes, in: Kim, D.Y., von Cieminski, G., Romero, D. (eds) *Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas into Action*. APMS 2022. IFIP Advances in Information and Communication Technology, vol 663. Springer, Cham.

[4] Hinrichsen, S., Riediger, D., Unrau, A, 2016. Assistance systems in manual assembly, in: *Proceedings of 6th International Conference on Production Engineering and Management*, Lemgo, Germany

[5] Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W., 2018. Digital Twin in manufacturing: A categorical literature review and classification, in: *IFAC-PapersOnLine*, Bergamo, Italy

[6] Tao, F., Zhang, M., Liu, Y., Nee, A., 2018. Digital twin driven prognostics and health management for complex equipment, in: *CIRP Annals*

[7] Lödding, H., 2014. Gedanken zu einem abgestimmten Management von Kosten, Zeit und Qualität, in: Schuh, G., Stich, H., *Enterprise-Integration. Auf dem Weg zum kollaborativen Unternehmen*, Springer, Berlin, Germany

[8] Erlach, K., 2020. Value Stream Design. The Way Towards a Lean Factory, Heidelberg, Germany

[9] Gunreben, C., 2019. Entwicklung eines Modells zur Fehlervermeidung bei Montageprozessen. Project Thesis (Supervisor: Brosche, J.; Examiner: Lödding, H.), Hamburg, Germany

[10] Glöckner, R., 2020. Entwicklung eines Gesamtmodells der Arbeitsproduktivität und der logistischen Zielgrößen, in: *Wissen schafft Innovation*, Hamburg, Germany

[11] Tietze, F., 2017. Analyse und Verbesserung der Arbeitsproduktivität in der Unikatproduktion, in: *Wissen schafft Innovation*, Hamburg, Germany

[12] Bertram, P., Birtel, M., Quint, F., Ruskowski, M., 2017. Informationsmodellierung zur Beschreibung manueller Tätigkeiten an Handarbeitsplätzen, in: Burghardt, M., et al. (eds) *Mensch und Computer*, Regensburg, Germany

[13] Niehaus, J., 2017. Mobile Assistenzsysteme für Industrie 4.0. Gestaltungsoptionen zwischen Autonomie und Kontrolle, in: *FGW-Impuls Digitalisierung von Arbeit 04*, Düsseldorf, Germany

[14] Apt, W., Schubert, M., Wischmann, S., 2018. Digitale Assistenzsysteme - Perspektiven und Herausforderungen für den Einsatz in Industrie und Dienstleistungen, Berlin, Germany

[15] Rost, R., 2021. Digitale Assistenzsysteme in der Industrie: Visualisierungskonzept, Hamburg, Germany

[16] Jahn, N., Jansen, T., Rost, R., Lödding, H., 2022. Disruption Management in One-Off Production with Collaborative Digital Assistance Systems. Benefits of an Integrative Approach with a Generic Data Model, in: *Schriftenreihe der Wissenschaftlichen Gesellschaft für Arbeits- und Betriebsorganisation (WGAB) e. V.*, Hamburg, Germany

[17] Soehner, G., Krohne, I., Goehlich, R., 2016. Entwicklung technischer Unterstützungssysteme für die Flugzeugfertigung - Roboter, Exoskelette und Chancen der Digitalisierung, in: *Fokus Mensch im Flugzeugbau, Gesellschaft für Arbeitswissenschaft e.V., Herbstkonferenz*, Dortmund, Germany

[18] Davis, F., 1986. A technology acceptance model for empirically testing new end-user information systems: theory and results, Doctoral dissertation. MIT Sloan School of Management, Cambridge, USA