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Case study analysis of laser-assisted Low-Cost Automation assembly

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Abstract: Highly connected Cyber-Physical Systems (CPS) are central elements for the Digital Factory of Industry 4.0. The integration of existing automation infrastructure with cost-efficient laser systems for worker guidance creates Low-Cost Automation (LCA) CPS that enable quality workplaces. Such human centric LCA CPS must be usability optimized. This paper presents the findings of three case studies focusing on the perceived efficiency, effectiveness and system usability of an LCA CPS laser-assisted assembly station in a shop-floor scenario. By using an inductive approach, design principles are derived that enable usability optimized LCA CPS to support acceptance and productivity.

Keywords: Low-Cost Automation, Cyber-Physical Systems, laser-assisted assembly, design principles, manufacturing systems, guidance systems, laser and digital factory.

1. INTRODUCTION

The Digital Factory of the Industry 4.0 is characterized by high connectivity of intelligent devices in a network of Cyber-Physical Systems (CPS) as presented by Bauer and Horváth (2014). CPS network horizontally with each other. Vertically connected CPS exchange data with on-premise or cloud-based solutions supporting the management of devices and analysis of data. At a first glance, highly connected CPS with advanced components seem incompatible with the concept of Low-Cost Automation (LCA). However, integrating existing automation technology with cost-efficient systems creates LCA CPS that offer opportunities for manufacturing companies, for instance, a gradual transformation towards the Digital Factory or the cost-efficient reconfiguration of production systems as identified by Bortolini et al. (2018). Many different industry branches use laser-assisted assembly systems due to their specific characteristics. For example, in aviation manufacturing or shipbuilding the contours can be displayed from large distance on three-dimensional objects. The laser lines are visible even in varying ambient light conditions and often form an additional level of detection and measurement. Merazzi et al. (2017) conclude that the combination of vision sensors with projection-based assistance achieves highest user value. Taubert et al. (2018) evaluate an exemplary set-up of such a system. Müller-Polyzou et al. (2019b) analyse the integration of laser-assisted assembly systems into Manufacturing Execution Systems (MES). Alternatives to laser-assisted assembly systems are head-mounted displays or video projection as outlined by Büttner et al. (2016). Addressing user needs can create LCA CPS that are not only simple and cost-efficient as described by Takeda et al. (2006) and Refa (2019), but also support high flexibility, versatility, reliability and user acceptance. Additionally, a human-centric design enables high-quality workplaces that meet the expectations of the future of work according to Wischmann et al. (2018).

2. RESEARCH FOCUS

In a recent project presented by Müller-Polyzou et al. (2019a), a laser system for worker guidance integrated into control components of a digital factory forms an LCA CPS for laser-assisted assembly. The evaluation of the technical integration shows that low latency times of the horizontal integration support the digital transformation towards a flexible and versatile production. The use of software controllers reduces system costs and increases reliability. The horizontal integration also enables a cost-efficient reconfiguration of the production system. The vertical integration into the cloud allows databased services that increase quality and productivity. The present work investigates the user dimension as this was not done in the aforementioned project. Therefore, this work considers three case studies, analyses and presents the perceived effectiveness, efficiency and system usability of an LCA CPS laser-assisted assembly station. First, the paper provides background information on LCS and laser projection systems. Next, it describes the technical environment of the Digital Factory including the case study test system. The following section includes the research methodology and implementation of the case studies. It is followed by the research results, their discussion and validation. Finally, the conclusion presents design principles and the outlook gives ideas for future projects.

Human-centric LCA CPS integrated in the Digital Factory are complex to research. Many factors influence the Human-

Computer Interaction (HCI) as outlined by Stephanidis et al. (2019). The boundaries between the factors are often blurry. The research presented in this paper focuses on the perceived effectiveness, efficiency and system usability influencing productivity and user acceptance (Fig. 1). The dimensions effectiveness, efficiency and user satisfaction are defined in ISO 9241-11 (2020) ergonomics of human-system interaction as the three guiding criteria. According to ISO 9241-116 usability comprises time during use, while user experience comprises the periods before, during and after use.

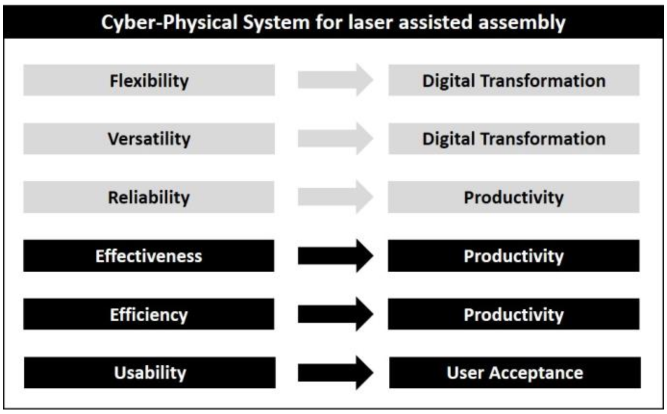

Fig. 1 CPS for laser-assisted assembly

In this research it is hypothesized that well-designed LCA CPS for laser-assisted assembly can reach high perceived effectiveness, efficiency and system usability values in support of high-quality workplaces for the future of work.

3. LOW COST AUTOMATION LASER ASSISTANCE

3.1 Low Cost Automation

LCA solutions for automation are developed using existing resources and standard components. This includes both the existing workforce and workstations. LCA can be optimized for high availability and short configuration times. The users play an essential role in LCA. They are often involved in the design and implementation. LCA for assembly tasks can be realized using existing automation technology components and cost-efficient laser systems for worker guidance. Advanced automation technology components such as Artificial Intelligence (AI) based modules for visual quality inspection can upgrade LCA systems. Thereby LCA CPS with comprehensive features can be created. Human-centric CPS provide modern workplaces for future-proof assembly.

3.2 Laser projection systems

Laser projection systems consist of a laser projector, laser reflector targets, power and data connections as well as a computer with a projection software. A digital work plan in the form of sequential laser projections on the assembly object guides the user through the work process. The main user interaction is to switch between the laser projections. Further functions are calibration procedures using the reflector targets and the loading of digital work plans. The projection is controlled via the Graphical User Interface (GUI) of the software or an Infrared (IR) remote control. However, Müller et al. (2018) conclude in a comparative analysis that voice recognition is the preferred method for system control. Laser projection systems can technically be integrated using TCP/IP interfaces.

4. TECHNICAL TEST ENVIRONMENT

4.1 Digital Factory

The Digital Factory of the Leuphana University consists of seven CPS that operate autonomously and form one production network (Fig. 2). The stations are equipped with industrial components for control, visualization and human-machine interaction. The configuration of the CPS and the networking of the components are defined in the Siemens Totally Integrated Automation (TIA) Portal. The laser-assisted assembly station is designed as one CPS. The manufacturing jobs are created at a separate station using an HMI. Each order is stored on an industrial type Radio Frequency Identification (RFID) transponder. The assembly status of the object is updated on the transponders during the production process. The connection to the Mindsphere cloud is realized using IOT2040 gateways.

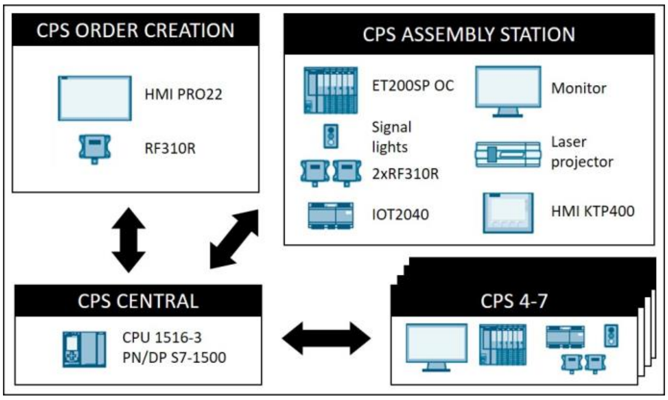

Fig. 2 Digital Factory with Cyber-Physical Stations

4.2 Test system

The test system is the CPS assembly station (Fig. 3). The station includes an aluminium substructure on which a monitor is mounted. The monitor shows the required assembly steps. Small load carriers are mounted within the reach of the user. The work surface can be equipped with holders for different mounting objects. The holders are 3D printed in a Fused Deposition Modelling (FDM) process. An HMI is integrated into the work surface and used to control the work process. The HMI communicates with the Programmable Logic Controller (PLC) and thus controls the laser projection. A signal light indicates the status of the assembly station. RFID transponders are used to read and document the assembly jobs.

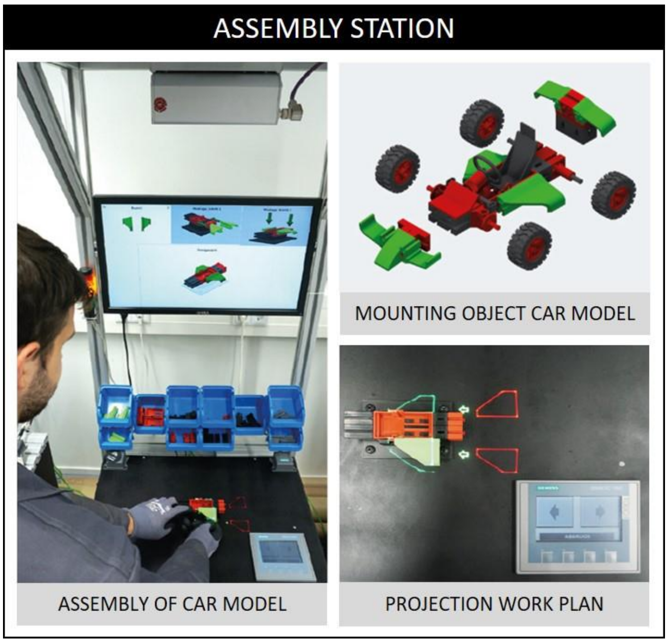

Fig. 3 LCA CPS for laser-assisted assembly

The assembly object is the car model Advanced Racer from Fischertechnik. The model can be built in 64 different variants. The user first defines a variant of the car model, which is stored as a variant code on the RFID transponder. The RFID transponder is processed at the assembly station as a manufacturing job and the corresponding work plan is loaded. The user is guided by the system through the commissioning of parts and the assembly process. Additional information is displayed on the monitor, which is synchronized with the laser projection. The small load carriers for the commissioning of the assembly parts are not indicated by the laser. The projection sequence of the work plan consists of polygons derived from CAD data. After completion of the assembly process the RFID transponder is updated with information from the assembly progress.

5. RESEARCH METHODOLOGY

5.1 Theoretical background of case study research

The case study method was selected for the analysis in order to investigate and explore individuals in the context of an assembly task in a manufacturing environment. Yin R.K. (2003) presents a case study as an empiric method that investigates a phenomenon within its specific context. The case study method is applicable in a situation in which a result relies on multiple sources of evidence. Furthermore, it benefits from prior research conducted. Criticism against case study research includes lack of rigor, a limited basis for scientific generalization and the comprehensive effort needed for implementation. However, Eisenhardt (1989) describes the process of theory building from case studies as novel, testable, empirical valid and well suited to new research areas. An individual structured observation with a single observer as a passive participant according to Saunders et al. (2019) was added to the case study to provide additional data. The case studies presented in this paper were designed to prove the hypothesis and to derive design principles for LCA CPS. The goal of the case studies was to obtain empiric data to provide a clear chain of evidence according to Service (2009) to confirm the findings. Multiple case studies embedded in the context were executed to increase rigor.

5.2 Qualitative and quantitative data gathering

Structured questionnaires were developed to collect qualitative data. The *long user questionnaire* gathers demographic data, attitude towards the unknown, experience in assembly and expectations towards assembly systems. It includes the System Usability Scale (SUS) questionnaire with ten questions with alternating positive and negative tone according to Lewis (2018). The SUS determines the perceived system usability. It can be used on small sample sizes with reliable results. Additionally, two questions from the After-Scenario Questionnaire (ASQ) described by Lewis (1991) were added to analyze the perceived efficiency and effectiveness of the system. Both SUS and ASQ are designed to be used immediately after completion of a test scenario. A five-point Likert scale without n/a option was applied. The questionnaire concluded with five open questions asking for improvement recommendations for the assembly station. The open questions target technical aspects such as the design of the work surface, information presentation and the HMI interface. The *observer questionnaire* was applied together with the long user questionnaire and was used among others to record the number of errors and positive or negative remarks during the test. The observer questionnaire also summarized the participants' appearance in terms of sovereignty, handling and overall structure of the task execution. The *short user questionnaire* used the three questions of the ASQ with a five-point Likert scale with n/a option to analyze the perceived effectiveness, efficiency and satisfaction with support information provided during the assembly task. Additionally, demographic data and the behavior of the user during testing in view of the ease of use of the system were noted. The questionnaire was optimized for short survey times. It took users usually up to three minutes to complete the assembly task, five minutes to fill in the long user questionnaire or alternatively one minute to complete the short user questionnaire. The observer questionnaire was completed during test execution by the observation manager.

5.3 Roles and responsibilities

Clear roles and responsibilities were defined for the case study implementation. The *test manager* was responsible for the operational execution of the case study including the technical well-functioning of the test system, the initial demonstration of the system, the management of the sample group and the closing of the case study. The *observation manager* analyzed and documented each participant individually during the test. The observation manager participated in the presentation of the test scenario and the observer's role was described in order to establish a comfortable test situation. The participants executed the case study and documented their experience in the user questionnaire. The expectation was formulated towards the participants to receive complete, spontaneous, non-biased and open-minded feedback.

5.4 Case study implementation

Two case studies Leuphana-1 and Leuphana-2 were executed at the Digital Factory of Leuphana University in Lüneburg Germany on December 18th, 2018 and June 11th, 2019. The sample groups consisted of students of technical courses. An additional case study Motek was performed from October 5th to October 8th, 2019 at the Motek trade fair for automation in production and assembly in Stuttgart, Germany. At the beginning of the case studies Leuphana-1 and Leuphana-2, the participants were informed about the research project in the form of a short presentation, followed by their written declaration of consent for participation and survey data processing. Afterwards the participants were introduced to the test system. The system operation was explained and demonstrated. Subsequently, the participants carried out the assembly independently. Meanwhile the observer filled in the observer questionnaire. After completion of the assembly task, the participants filled in the long user questionnaire. The Motek case study was conducted with a random selection of trade visitors following a brief system presentation by the test manager. Afterwards the participants filled in the short user questionnaire. The observation was performed by the test manager. The participation in the case studies was voluntary with no incentives provided. The case study data was analyzed using IBM SPSS Statistics Version 26.

5.5 Sample groups

The sample group of the case study Leuphana-1 consisted of eleven participants. All questionnaires were valid (n1=11). Nine participants (81,8%) were male and two (18,2%) female. Nine participants (81,8%) were 25 to below 55 years, one participant (9,1%) 55 to below 65 years and one participant (9,1%) below 25 years old. All participants stated that they hold an academic degree. Being asked for their attitude seven participants (63,6%) stated that they prefer, “the known to the unknown”. Five participants (45,5%) quote that they have experience in industrial assembly while six participants (54,5%) are unexperienced in assembly.

The sample group Leuphana-2 consisted of eleven participants. All questionnaires were valid (n2=11). Eight participants (72,7%) were male and three (27,3%) female. Nine participants (81,8%) were below 25 years and two participants (18,2%) 25 to below 55 years old. Seven participants (63,6%) indicated that they do not have a professional job qualification, three (27,3%) are with a job qualification and one (9,1%) participant is in education. No participant had an academic degree. With regards to their attitude six participants (54,5%) stated that they prefer “the unknown to the known”. Nine participants (81,8%) stated that they have no experience in industrial assembly while two participants (18,2%) were experienced in assembly.

The sample group of the case study Motek consisted of 24 participants. 23 questionnaires were valid (n3=23). All participants were male. Eleven participants (47,8%) were below 25 years, eleven participants (47,8%) 25 to below 55 years and one participant (4,4%) 55 to below 65 years old.

5.6 Sample group discussion and limitations

Typical tasks of assembly operators include production steps of pre-, partial or final assembly of components, modules and end products. When selecting the sample group, it was assumed that technical students and visitors of a subject matter trade fair had an affinity, open-mindedness and possibly experience with assembly tasks. The need for open-mindedness towards new technologies is described by the German Federal Employment Agency (2019a) as a prerequisite for assembly jobs. The number of employees in Germany liable to social security are reported on a quarterly basis. The March 2019 figures for the economic group 27275 were analyzed. This group represents the employees working in the production of household appliances which is characterized by a high degree of manual assembly tasks. According to the German Federal Employment Agency (2019b) 71,8% of the employees were male and 28,2% female. 7,7% of the employees were below 25 years old. 69,1% were 25 to below 55 years old, 23,0% 55 to below 65 years and only 0,2% were 65 years or older. 19,9% were without a professional job qualification. 62% had a professional job qualification and 16% hold an academic degree. The education level of the remaining 2,1% is not known.

Although the sample groups Leuphana-1 and Leuphana-2 consisted of students, the sample groups matched the high share of men in manual assembly. Additionally, seven participants (31,8%) of the sample groups had already experience with industrial assembly. Ten participants (45,5%) preferred the “Unknown” which is an indicator for open-mindedness according to Nov et al. (2008). However, the sample groups Leuphana-1, Leuphana-2 and Motek showed a higher degree of young participants. The share of participants below 25 years was 39 percentage points higher, the share of 25 to below 55 years was 20,2 percentage points lower and the share of 55 to below 65 year old participants was 18,5 percentage points lower compared to the labor market figures. Therefore, the sample groups Leuphana-1, Leuphana-2 and Motek did not reflect the exact labor market figures. An additional limitation is seen in the higher education of the participants of Leuphana-1 and Leuphana-2 compared to the labor market figures. The share of participants with academic degree was 34 percentage points higher and the share of participants with professional job qualification was 48,4 percentage points lower in the sample groups. The total number of participants (n=n1+n2+n3=45) was high. Although, an additional case study with industry assembly workers would strengthen the research data.

A further limitation is the selection of the research method. The case study data form a limited basis for scientific generalization even with multiple case studies being executed to increase rigor. The results need to be discussed in the situational context of the test scenario.

6. RESEARCH RESULTS

6.1 Case study Leuphana-1 and Leuphana-2

In total 58 expectations on assembly systems were stated by the participants (including equal statements). The expectations were manually clustered using a mind map created with XMind Version 8. The three categories Human-Machine-Interface (36,2%), Machine-Human-Interface (MHI) (29,3%) and system requirements (34,5%) presented in Table 3 were derived. The categories Human-Machine-Interface and system requirements were subdivided into the dimensions effectiveness, efficiency and usability (Fig. 1). Table 1 additionally presents exemplary user comments.

Table 1. Expectations on assembly systems

Categories	Dimensions	User comments
Human-Machine-Interface	Effective-ness (4 items)	easy to understand for unskilled, manufacturing without prior knowledge
	Efficiency (1 item)	simplifies learning of work steps
	Usability (16 items)	precise instructions, guiding, illustrating assembly well, detailed support
Machine-Human Interface	Usability (17 items)	intuitive/ easy to use, easy to understand, self-explanatory, simple, user friendly
System require-ments	Effective-ness (5 items)	points out non-obvious details, automatic error detection, fault indication
	Efficiency (8 items)	achieves time savings, not disruptive, efficient, error-free, no time-delays
	Usability (7 items)	ergonomic, increase work safety, relief, no time pressure, supportive

The expectations were almost equally distributed in the three categories. However, on dimension level usability (69%) prevails effectiveness (15,5%) and efficiency (15,5%). The system usability was surveyed in more detail applying the SUS. The average agreement values and standard deviation for the SUS questions are listed in Table 2. The agreement values varied because of the alternating positive and negative tone of the questions. The standard deviation of the first question was relatively high. A root cause analysis on the research data showed that two participants had distinct problems with the assembly part commissioning process.

Table 2. Average agreement values [A] on a scale between zero (strongly disagree) and four (strongly agree) and standard deviation [σ]

n1+n2, valid 22	A	σ
I can imagine myself using the system regularly.	2,09	1,269
I think the system is unnecessary com-plex.	0,45	0,739
I think the system is easy to use.	3,18	0,733
I think I would need technical support to use the system.	0,82	0,795
I think the systems functions are well integrated.	3,00	0,756
I think there are too many inconsistencies in the system.	0,73	0,767
I can imagine that most people learn to use the system quickly.	3,77	0,429
I think the operation is inconvenient.	0,59	0,796
I felt confident using the system.	3,32	0,716
I needed to learn a lot before I could work with the system.	0,32	0,568

An average SUS value of 81,1% with a standard deviation of 10,2 was calculated as shown in Table 3. The SUS value was 29,6 percent points higher compared to a case study focusing on user interaction methods presented by Müller et al. (2018) which served as a control group. The perceived effectiveness reached a high agreement value A of 3,23 and the perceived efficiency a high agreement value of 3,05 (on a scale between zero and four) with standard deviations of 0,869 and 0,95 as shown in Table 3. A total of 81,9% of the participants of the case studies Leuphana-1 and Leuphana-2 agreed/strongly agreed with the statement “Altogether I am satisfied with the simple completion of the tasks.”, respectively 77,3% with the statement “Overall, I am satisfied with the time it took to complete the tasks.”.

Table 3. Results Case Studies Leuphana 1 and 2

		SUS	Perceived effectiveness	Perceived efficiency
n1+n2	Valid	22	22	22
Mean		81,1364	3,23	3,05
Std. Deviation		10,19825	0,869	0,950

Finally, the participants provided feedback and improvement recommendations. Twelve participants (54,5%) replied that the mounting base for the assembly object fulfilled their personal needs. Three participants (13,6%) suggested to increase the distance of the mounting base to the workstation surface. Furthermore, the participants suggested: a) to differentiate the mounting base and assembly object in color b) to install a mechanism that releases the object after successful assembly c) to reduce the force required to fix the object to the mounting base. Sixteen participants (72,7%) said that the HMI touch panel for controlling the projection is user friendly. Four participants (18,2%) criticized the position of the HMI. They mentioned that they needed to look up and down and move their hands outside the comfort zone. It was also recommended to improve the contrast and readability of the monitor. Eighteen participants (81,8%) were satisfied with the amount and structure of information provided on the monitor. The remaining participants suggested: a) to use the laser to indicate assembly parts in the load carriers b) to provide more detailed information c) to secure better visibility on the monitor. Finally, seven participants (31,8%) mentioned that they did not miss any function in the implementation. Five participants (22,7%) wanted automatic quality control features. Four participants (18,2%) recommended part indication in load carriers. Furthermore, the participants suggested: a) moving laser projections b) specific messages during the laser calibration. Two participants suggested a better ergonomic position of the monitor and one proposed larger objects for better visibility.

The observation of the participants during the execution of the case studies showed positive results. No critical statements and only one single frustration statement were expressed. Twenty-one participants (95,5%) did not show difficulties using the system. Only one participant seemed overwhelmed. No participant showed signs of desperation. Fifteen participants (68,2%) performed the mounting task without any error, six participants (27,3%) with only one error. Therefore 95,5% of the participants performed the mounting task with up to one error as presented in Table 4.

Table 4. Number of assembly errors observed

		Frequency	Percent	Cumulative Percent
Valid n1+n2	0	15	68,2	68,2
	1	6	27,3	95,5
	2	1	4,5	100,0
	Total	22	100,0	

The laser-assisted assembly station was reliable. Only one restart was necessary due to an interruption of the laser calibration process. Parts commissioning was second source of error. Participants seemed to require additional support. The observation coincides with the improvement options mentioned by participants. It is noteworthy that no comments were made regarding laser safety.

6.2 Case study Motek

All participants of the case study Motek were satisfied with the simple completion of the task as shown in Table 5.

Table 5. Agreement with statement for effectiveness

		Frequency	Valid Percent	Cumulative Percent
Valid n3	Strongly agree	13	56,5	56,5%
	Agree	10	43,5	100,0%
	Total	23	100,0	

The participants were also satisfied with the time needed to complete the task. Table 6 presents the high agreement values.

Table 6. Agreement with statement for efficiency

		Frequency	Valid Percent	Cumulative Percent
Valid n3	Strongly agree	5	21,7	21,7
	Agree	18	78,3	100,0
	Total	23	100,0	

87% of the participants agreed/strongly agreed that the level of support information provided during the completion of the task was satisfying. Three participants (13%) were neutral on the statement as shown in Table 7.

Table 7. Agreement with statement for support information

		Frequency	Valid Percent	Cumulative Percent
Valid n3	Strongly agree	5	21,7	21,7
	Agree	15	65,2	87,0
	Neutral	3	13,0	100,0
	Total	23	100,0	

7. DISCUSSION AND VALIDATION

The expectations on assembly systems stated by the participants match with the dimensions effectiveness, efficiency and usability. They can be equally categorized in HMI, MHI and system requirements. Most of the expectations (69%) were usability related highlighting the need for a user-centric system design. The LCA CPS for laser-assisted assembly reached a SUS of 81,8% indicating a good to excellent system usability according to Lewis (2018). The majority of the participants perceived the overall task fulfillment with the system as effective (A=3,23 out of 4) and efficient (A=3,05 out of 4). The findings are confirmed by the observation during the case studies. The observation shows that 95,5% of the participants did not have difficulties using the system. No critical statements were made by the users during task completion. Furthermore, the ease of use is reflected by the low error rates. The participants were not trained to use the system. Still, 68,2% of the participants performed the task without any errors and 27,3% with only one error. Overall, the Motek case study confirmed the findings of the Leuphana-1 and Leuphana-2 case studies. The perceived effectiveness and efficiency reached 100%. System usability in terms of information provided during task fulfillment reached a high value of 87%.

8. CONCLUSIONS

An instantiation of an LCA CPS laser-assisted assembly station addressing the identified needs of manufacturing business was evaluated in three case studies. A corresponding hypothesis was formulated addressing business needs. Two case studies were conducted in the Digital Factory of the Leuphana University and one at the Motek trade fair. Applicable knowledge was taken into consideration during the design of the test system. The results of the case study research were high values of perceived effectiveness, efficiency and system usability for the LCA CPS laser-assisted assembly station in the manufacturing scenario.

The hypothesis that well-designed LCA CPS for laser-assisted assembly can reach high perceived effectiveness, efficiency and system usability values supporting high-quality workplaces for the future of work is thereby confirmed. Design principles (DP) are formulated using an inductive approach according to Dresch et al. (2015). DPs add to the existing knowledge base as shown by Hevner et al. (2004):

DP 1: Analyze your automation technology infrastructure and low-cost systems for manual assembly available on the market. Select systems that can be integrated with low-effort and preferably own resources. Integrate the system into your automation processes creating an LCA assembly system.

DP 2: Secure a reliable horizontal integration with sufficient technical performance for a good overall user experience. A seamless integration supports the usability and acceptance of the LCA assembly system.

DP 3: Upgrade the LCA assembly system with selected automation components that provide rich features creating modern workplaces. Investigate the specific value that can be created by a vertical integration.

DP 4: Design the LCA CPS assembly systems according to ergonomic guidelines and best practices. Involve users in the design of the HMI, MHI interfaces and the work area. Optimize systems for simplicity.

DP 5: Optimize the work process for effectiveness and efficiency. Pay special attention to the information density and the sequence of work steps of the digital work plan. The interaction of the user with the HMI, the information provided by the MHI and the assembly works must be well synchronized.

The instantiation of the test system can be refined and improved in future works considering the valuable recommendations provided by the participants. Additional case studies, for instance with alternative technologies, would strengthen the rigor and thereby the grounding of the design principles in the knowledge base.

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Appendix A. SUPPORTING DOCUMENTS

The case study questionnaires are available for download at https://www.researchgate.net/profile/Ralf_Mueller-Polyzou/projects.

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