Design of Industrial Workplaces to relieve Workers when Interacting with Joint-Arm-Robots

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List of Abbreviations

Abbreviation	Description
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AIWS	Assisting-Industrial-Workplace-System
BEF	Biologically Effective Lighting
CEA	Research Group CEA Computational Engineering and Automation
CPS	Cyber-Physical-Systems
DIN	German Institute for Standardization
EEG	Electroencephalography
ENP	Extended Network Plan
ERP	Event-Related Potential
EWI	EEG-based Workload Index
FFT	Fast Fourier Transformation
FG	Focus Group
GUI	Graphical User Interfaces
HCD	Human-Centred Design
HF	Human Factor
HFE	Human Factor Engineering
HMI	Human-Machine Interaction
HMS	Human-Machine Systems
HOF	Human and Organisational Factors
HRC	Human-Robot Collaboration
HRI	Human-Robot Interaction
I4.0	Industry 4.0
IDE	Integrated Design Engineering
IEA	International Ergonomics Association

IIoT	Industrial Internet of Things
IoT	Internet of Things
ISO	International Standards Organisation
LED	Light-Emitting Diode
ML	Machine Learning
NASA TLX	NASA Task Load Index
NN	artificial Neuronal Network
NPD	New Product Development
ORB	Oriented fast Rotated Brief
RGB	Red, Green and Blue
ROS	Robot Operating System
SAPPS	Self-Adapting-Production-Planning-Systems
SVM	Support Vector Machine
UI	User Interface
WbL	Work-by-Light

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Abstract

A comprehensive understanding of the needs of the user is required to design adequate workplace systems in general, but especially in the highly digitised area of industry where operators are interacting with autonomously operating machines.

There is little knowledge in design criteria for professionals to enable adequate developments of system design for Human-Machine Interaction, e.g. Human-Robot Collaboration regarding the effects of design decisions to all three levels of Human Factors, i.e. physiological, cognitive and organisational limitations. Moreover, there is little known about objective measurement procedures that evaluate whether the operator subjectively perceives the workplace system design as assistance and improvement.

The research presented in the following is affiliated with the scientific discipline of Human Factors Engineering and focuses on the evaluation of Human Factor issues within the digitised industry.

Based on broad theoretical and empirical investigations, the results of this research extend our knowledge of adequate Human-Centred Design by providing reliable, powerful design criteria for workplaces where operators interact with machines/collaborate with robots, but also an overall technique, the Objective Workload Detection Method, for evaluation of the effectiveness of design investigation focusing on cognitive stress relief.

Through the application of this method within a controlled experiment, the validation of the derived design criteria was confirmed. The study significantly shows how the cognitive workload can be relieved by an assisting environment.

This work also gives one best-practice design example of a self-adapting workplace system for hybrid Human-Robot Teams. Following the Human-Centred Design method, the concept of Assisting Industrial Workplace System for Human-Robot Collaboration has been successfully developed as a flexible hybrid unit design. The prototype is related to a real-world scenario from the aerospace industry and the demonstrator was implemented within a laboratory set-up.

This work seamlessly applies techniques from interdisciplinary science fields, e.g. Engineering, Neuroscience, Gestalt theory, and Design. Equally, the design criteria and the evaluation method will support professionals from varied disciplines to succeed in the creation process of future system-designs by giving a clear indication of future Human-Centred Design research.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institutes of learning.

Some sections of this work have been published in advance in:

Ender, J., Wagner, J. C., Kunert, G., Guo, F. B., Larek, R., & Pawletta, T. (2019). Concept of a self-learning workplace cell for operator assistance while collaboration with a robot within the self-adapting-production-planning-system. Informatyka, Automatyka, Pomiary W Gospodarce I Ochronie Środowiska, 9(4), 4-9. DOI 10.35784/iapgos.36

Ender, Johanna; Wagner, Jan Cetric; Kunert, Georg; Larek, Roland; Pawletta, Thorsten; Guo, Fang Bin. (2019), Design of an Assisting Workplace Cell. IIPhDW19. International Interdisciplinary PhD Workshop. Wismar. DOI 10.1109/IIPHDW.2019.8755412

Ender, Johanna; Guo, Fang Bin; Jenkinson, Ian; Larek, Roland; Waraich, Atif. (2018), Workspace design for Human-Machine-Interaction. Faculty Research Week. Liverpool John Moores University. Liverpool. DOI 10.13140/RG.2.2.28417.15206

Ender, Johanna; Guo, Fang Bin; Larek, Roland. (2018), Design of an intelligent workplace system for human-machine-interaction in the digitized industry. Journal of Applied Mechanical Engineering - V7. 2nd Int. Conf. on Advanced Robotics, Mechatronics and Artificial Intelligence & 3rd Int. Conf. on Design & Production Engineering. Valencia. DOI 10.4172/2168-9873-C2-020

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The list includes references to joint authorship of published materials which might have been included in a thesis submitted by another student to this university or any other university or other institutes of learning.

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This book is for anyone who believes that collaboration
without borders creates a better future.

Chapter 1. Introduction

The International Ergonomics Association (IEA) defines the *'Human Factors and Ergonomics'* as a scientific discipline that focuses on understanding people's needs, abilities, and limitations with the purpose of designing adequate interaction systems (International Ergonomics Association 2020). Since the integration of autonomous operating machines, especially collaborating robots within shared workplaces with human operators, Human Factor Engineering (HFE) is gaining in importance as a field of study. The introduction of hybrid Human-Machine Teams and higher dynamics of processes have created additional stress factors negatively influencing the well-being of the operator. The study investigates the impact on the operators within the digitised industry and targets to minimise the strain within Human-Machine Interaction (HMI)[1] and Human-Robot Collaboration (HRC)[2]. The following section introduces the general problems addressed in this project, in terms of aim and objectives of the research, an overview of the thesis, an academic network, industrial links and contributions of this project.

1.1 Background of Study and Motivation

Human-centred and/or user-friendly workplace/environments have been attracting considerable attention due to the increasing level of complexity/difficulty of the working tasks. The integration of shared workplaces of operators interacting with joint-arm-robots and

[1] The abbreviation HMI will be used to refer to the interaction and communication between human and machines (Bendel 2019; Johannsen 2007). In many cases, the machine is a computer or contains information and communication technologies. Moreover, there is a close relationship and significant overlap with human-computer interaction.

[2] A generally accepted use of the term HRC refers to robots assisting the human operator, by complementing the operator's capabilities and relieving them of strenuous tasks (KUKA AG 2020). Moreover, HRC is an interdisciplinary research area involving scientific fields of classical robotics, cognitive sciences, and psychology (Bauer et al. 2008). In the context of the industrial environment, the term Human-Robot Collaboration applies to any situation where robots work directly alongside humans without safety barriers on the manufacturing floor. The work is carried out simultaneously to achieve a common goal (Bauer et al. 2016).

autonomous operation machines in automation environments is in accordance with the requirements of the Industry 4.0 (I4.0) initiative (German Federal Ministry of Labour and Social Affairs 2017).

1.1.1 Higher dynamics based on the Integration of Cyber-Physical Systems

A major reason for the change in the way of working in the industry is the integration of machines, computers and smart devices (Geisberger and Broy 2012; Acatech 2016). Contemporary industrial workplaces consist of operators, computers, robots and autonomously operating machines. Cyber-Physical-Systems (CPS)[3] especially those including HMI and in particular involving interaction with robots, are increasingly integrated into the working process (Molzow-Voit et al. 2016; Westkämper et al. 2013; Lorenz et al. 2015). These systems contain autonomous operating machines and storage systems, and typically a continuous exchange of information (Acatech 2013). In the future, especially monotonous, non-ergonomic and health-damaging activities will be done by robots. To achieve the known advantages for the industry the integration of workplaces for HRC is sought. To take advantage of both collaboration partners, the combination of the specific abilities of human and robot must be harmoniously combined and used within the production, assembly or maintenance process. Figure 1 shows the competence profiles of human operator and robot and draws a comparison between the application profiles of classic industrial robots and collaborative robots.

The integration of workplaces where humans and robots interact to achieve a common goal is beneficial when it is ensured that the specific capabilities of the robot, such as its accuracy, speed and strength, are applied to assist the operator in fulfilling the work assignments. Nevertheless, changes in the process and unforeseen, previously undefined situations, pose a challenge for the machines. However, the competence profile of humans, e.g. sensitivity and wealth of experience compensates for this deficit (Buxbaum 2020). The operator remains the most flexible entity within the CPS (Gorecky et al. 2014). Finally, and of importance, is the inherent ability of humans to find creative solutions.

[3] Among others, the term CPS is defined by Baheti and Gill (2011) to refer to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities.

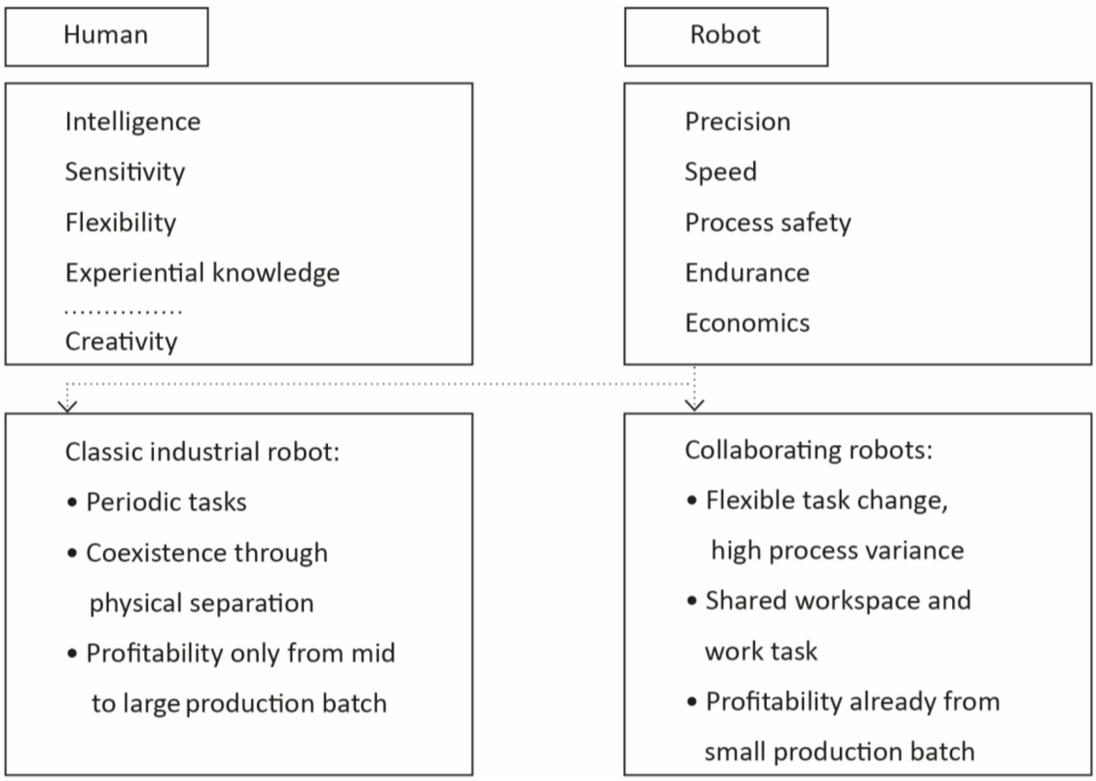

Figure 1 - Complementary competence profiles of the human operator and the robot. Adapted from: TCW (2016). No Creative Commons Licence.

The digitalisation of the industry has introduced new forms of interaction systems incorporating smart glasses, smartphones and tablet computers into the work place (Westkämper et al. 2013; Acatech 2013). The next decade will show how the interaction of humans and robots will change into a collaboration system. The ever-evolving possibilities of robotics stimulates the desire to interact efficiently with the robot through gestures, speech and touch.

Joint-arm-robots are finding more and more complex fields of application. As well as being used as a classic industrial robot, joint-arm-robots are now being integrated with operators as a *'helping hand'*. This is enabled through a new generation of robots, which are lightweight with sensitive sensors gently assisting the operator in a manual task. This results in a highly productive and automated manufacturing process. Figure 2 illustrates the five evolutionary stages of interaction between humans and robots (Bauer et al. 2016) from cell to collaboration.

These are:

- Cell: The action spaces of humans and robots are separated from each other by fences. The human operator assumes control and monitoring tasks.
- Co-existence: The action spaces of humans and robots are separated from each other by safety mechanisms like security sensor systems. Human operators and robots primarily work alongside each other to solve tasks separately.

- Synchronized: Robots and operators share a workspace, but only one interaction partner is actively working at a time
- Cooperation: Humans and robots share the action space and work in parallel to fulfil their subtasks.
- Collaboration: Humans and robots share the workspace and work together, simultaneously to achieve a common goal.

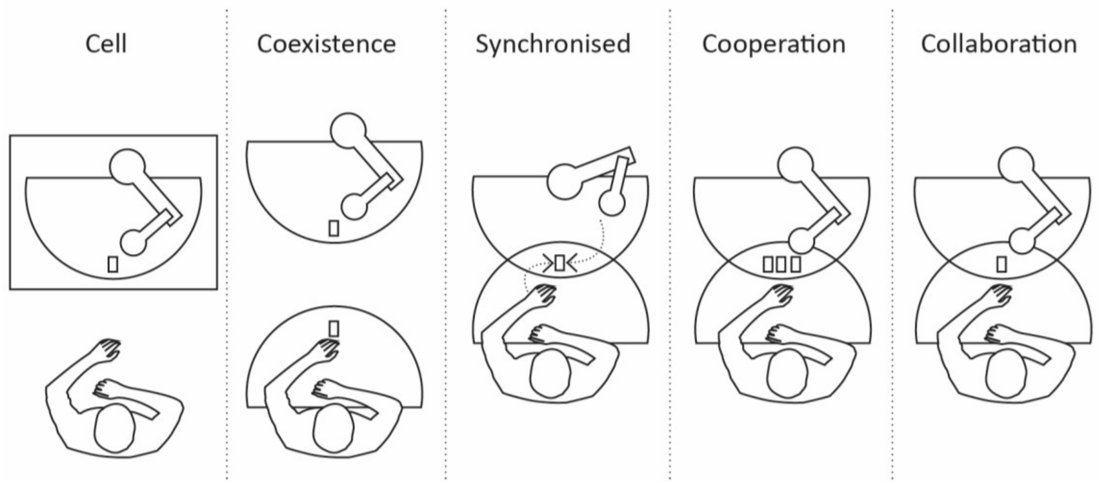

Figure 2 - The evolutionary stages of the interaction between human and robots. Robot's workspace, Operator's workspace and shared workspace. Adapted from: Bauer et al. (2016). No Creative Commons Licence.

Currently, safety measures such as fences are required to ensure a strict separation between the operator and autonomously operating robots. In the future, safe and comfortable collaboration with robots is sought (Stark et al. 2018; Bauer et al. 2017). As further development of the coexistence, Onnasch et al. (2016) classified two other forms of Human-Robot Interaction (HRI): cooperation and collaboration. Within the cooperation, humans and robots work towards a higher common goal. However, the actions are not directly dependent, as there is still a clear division of tasks between human and robot. Within the collaboration, operator and robot pursue a common goal. In contrast to cooperation, partial goals are also pursued together in this case.

1.1.2 Challenges at Workplaces for Human-Machine Interaction (HMI) and Human-Robot Collaboration (HRC)

The degree of complexity of tasks for employees increases with the growing demand for individual solutions and increasing mass production. Hybrid Human-Robot Teams offer significant benefits to react to volatile markets, but the successful integration of shared HRC-workplaces still faces many challenges for the successful integration. A most significant factor is the acceptance of the operator of this system design. Acceptance arises from the application of *'good design'* since good design makes a product usable and understandable for the user (Rams 2014). For instance, if the workplace system with the integrated robot is positively experienced as a service device, its integration will succeed.

Knowledge of product design focusing the fulfilment of user needs, e.g. regarding Human Factor (HF)[4] issues like ergonomics, cognitive processes and organisational integration is applied to develop the workplaces of modern offices. Nevertheless, knowledge from the field of interior and product design concerning HF in their three dimensioned issues is widely not transferred to the environments of contemporary industrial workplaces. Compared with the designs of contemporary office workplaces, the operators working with autonomous machines and robots within the digitised industrial environment are still confronted with several major challenges.

Joint-arm-robots are not moving like a human co-operator and interpretive characteristics such as facial expressions and gestures are missing. The operator has to focus a major part of his attention to the robot in order not to disturb its range of motion. This hinders rapid cognitive processing, which is needed to fulfil the working task correctly and safely. As the cognitive perception performance is already troubled by the high dynamics resulting from the characteristics of the working tasks accompanying the digitised industry, the workplace systems themselves are loaded with information signals.

As industrial workplaces are typically hazardous environments, visual and acoustic signals are utilized as warning signs to increase the safety of the operator. However, human brains are limited to the level of perception of those signals – only a limited number of signals can be perceived in parallel. High diversity and the number of cognitive stimuli lead to perception leaks. Important information can be overlooked. The operator tries to overcome this effect by increased effort and focus which finally leads to high strain. In the long term this constant strain negatively affects the health of the operator. Furthermore, this leads to human error, which it is crucial to prevent within a safety-critical environment.

In order to respond to the increasing complexity and resulting strain to the operator, human-centred assistance systems play a growing role in today's working world. For the employee, relief of strain is required at all levels in the corporate structure, e.g. using digital assistance

[4] The term ergonomics (or HF) is defined by the IEA as follows: Ergonomics (or HF) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance (International Ergonomics Association 2020). The terms ergonomics and HF are often used interchangeably or as a unit.

systems in the form of simulation systems or through machines supporting manual tasks. Once those assistance systems are experienced by the user as an advantage, barriers against the successful integration will be overcome and will enable the industry to adjust accordingly.

1.2 Research questions

Currently, greater attention is paid to the nature of work and workplaces within the digitised industry due to the increasing complexity of work tasks. The operators are under additional strain as a result of the range of highly dynamic processes and due to the integration of joint-arm-robots and autonomous operating machines. This research seeks to answer the following questions:

- What are the main hindrances toward the integration of joint-arm-robots working collaboratively with operators on manual montage/maintenance tasks?
- How can cognitive strain while interaction with a joint-arm-robot be objectively detected?
- How can a theoretical framework support the design of workplaces for HRC, specifically the collaboration with joint-arm-robots, and how should it be applied to face real-world circumstances?

The theoretical analysis indicates that there have been few studies on how a holistic view on HF influences the design of workplaces for HRC (see Chapter 2 Literature Reviews in the Field of Study). Furthermore, a comprehensive, systematic solution for industrial workplaces particularly that considers HF needs within HRC is widely not known and a specific application regarding production workplaces is missing.

1.3 Aim and Objectives of this Research

This research aims to fill in the gap of designing industrial workplaces for assisting Human-Robot Teams and initiates as a reference project with the claim to be a role model that meets the requirements of the digitised industry. The framework will enable the systematic design and development of the HMI supporting collaboration with joint-arm-robots.

For this purpose, the research is built upon a methodological approach which is oriented to the operator's needs. Thereby, the intersection of knowledge from scientific research, user-oriented product design and industrial engineering add up to suit the development of this research.

The aim will be achieved through the following objectives:

1. Analysis and Identification of HF issues and their impact on the workplace design within the digitised production processes, in terms of physical, cognitive and organisational limitations;
2. Investigation into the implementation of HRC, specifically operators working collaboratively with joint-arm-robots in industry:
3. Derivative of design criteria for workplace design that integrates the implementation of joint-arm-robots;
4. Development of a design concept for workplace design that integrates the implementation of joint-arm-robots. The concept will be based on the criteria (4);
5. Testing and evaluation of the proposed design criteria on a demonstrator;
6. Development and evaluation of an Objective Workload Detection Method regarding operator’s perceived cognitive strain.

This work combines applied and theoretical approaches to discover/understand the operator-needs in workplace design for HMI/HRC. A real-world scenario from the aviation industry, which demonstrates numerous similarities with other sectors of the German high-tech industry in terms of its structures and processes, is taken as a case-study.

In this research, the work has focused on the integration of workplace design to support manual montage tasks within the digitised industry that are solved by Human-Robot Teams.

1.4 An Academic Network and Industrial Links

1.4.1 The International Multidisciplinary Supervision Team

This is a PhD research project that has been supervised by an international and multidisciplinary team including Dr Fang Bin Guo[5] and Professor Dr Ian Jenkinson[6] from the Faculty of Engineering and Technology, Liverpool John Moores University, Great Britain,

[5] Dr Fang Bin Guo is a senior industrial designer with experience in Product Design Engineering. Dr Guo held a PhD degree in the field of Industrial Design.

[6] Professor Dr Ian Jenkinson held a PhD degree in the field of neuronal networks in the field of industrial robot systems.

and Professor Dr.-Ing. Roland Larek, M.BC.[7] a professor from the Hochschule Wismar - University of Applied Sciences: Technology, Business and Design, Wismar, Germany.

The research has been supported/funded by the Hochschule Wismar for the establishment of a laboratory and a research fellowship, a multidisciplinary team of the Production Technology Laboratory, in the Faculty of Engineering at the Hochschule Wismar. The research has also been supported by the researchers of the Research Group Computational Engineering and Automation (CEA) led by Professor Dr.-Ing. Thorsten Pawletta[8], who assisted this project by framing the research works context.

Likewise, a number of students from the Hochschule Wismar were invited/participated within a variety of experiments during the study. The author has also participated in supervising a master's student: Mr Daniel Luthardt for his course project and master's thesis preparation.

1.4.2 The Links of Industry

Aligning with the academic collaboration, this research has also benefited from a variety of industrial links that include small/medium-sized businesses and global players, and from extensive fields and great potentials within the digitised industry.

1. Aero-Coating GmbH: a German aerospace supplier in Wismar, which provided insights/expertise in the development of workplace design, re interactions between operators and robots. The company offered some challenges on currently existing workplace design aimed at supporting maintenance and manufacturing of material for aeroplanes as an application scenario for this research.
2. The German aerospace manufacturer Lufthansa Technik AG and Airbus in Hamburg, and the metal construction manufacturer Mebak Metallbau GmbH in Schönberg have both offered opportunities for the author to present the research questions re the challenges and potential of the hybrid human-robot workplaces and discussed questions on site.
3. The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM at Stade in Germany, assisted in the analysis of the challenges and opportunities raised from hybrid human-robot workplaces. Likewise, the headquarters of Franka Emika GmbH in Munich, Germany, has helped during the analysis phase that demonstrated the strong potential of lightweight robotics for collaboration with humans.

[7] Professor Dr.-Ing. Roland Larek, M.BC. held a doctoral degree in the field of manufacturing theory/factory planning.

[8] Professor Dr.-Ing. Thorsten Pawletta held a doctoral degree in the field of theory, methods and ontologies in modeling and simulation.

4. Advice has also been provided by entrepreneurs and scientists from the regional Expert Group Robotics & AI, Mecklenburg-West Pomerania, held by the Chamber of Commerce and Industry in Rostock.

   - Experts of the Ministry of Energy, Infrastructure and Digitization in Germany and researchers of scientific institutions from the Fraunhofer Institute for Computer Graphics Research IGD and the Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock Germany participated within this research, they provided advice/insights in terms of the new trends, existing challenges and scientific findings which framed this research aim and objectives.

   - PLANET artificial intelligence GmbH, a member of the expert group in Rostock, Germany, offered advice resulting from potential application fields of Artificial Intelligence (AI).

5. In affiliation to the expert group, the author has also visited the Danish Cluster for robotics and automatization, located in Odense (Denmark), undertaking research in a variety of companies and consulting insights of robotic systems development to support the digital transformation of the industry.

   Furthermore, a field trip has also been made to the Start-Up Hub in Odense to communicate with researchers and professionals on topics re developing novel robotic systems and applications, these include Mobile Industrial Robots A/S, Universal Robots A/S and Gibotech A/D that presented diverse hybrid teams of robots working with operators.

Moreover, interviews with scientists and professionals from industry have been undertaken. Interviewees are design practitioners and engineers who work in design for HMI. These include Dr Elias Knubben from Festo in Esslingen (Germany), who discussed the value of workplace design within digitised industry; Dipl.-Psych. David Kremer, Fraunhofer Institute for Industrial Engineering IAO in Stuttgart (Germany), who shared his knowledge on challenges and potential of workplace design affiliated to the field of robotics and digitalisation. Dipl.-Des. Andreas Hackbarth discussed his insights into the changing role of industrial design and its impact in the future workplace/environment design.

The research was funded by the Walter Blohm Stiftung due to the novelty of the study that thematically connects knowledge from science to real-world applications within aerospace industry.

1.5 Overview of the Thesis

The process of the knowledge-focus within this research consists of four methodological stages: discover, define, develop and deliver (see Figure 3) and the thesis is organised into six key chapters.

1.5.1 Discover

Chapter 2 – This chapter introduces the field of joint-arm-robots within the automated industry. Afterwards, it changes the focus from technology-oriented to the human-centred perspective and introduces the field of interaction design. Moreover, this chapter gives an analysis of the issues relating to HF in terms of physical, cognitive and organisational limitations in the design of the industrial workplace. It reviews existing knowledge in the field of industrial workplace design and identifies the place of this research in filling current gaps in knowledge. The chapter identifies issues which hinder the assistance of the operator within hazardous and highly dynamic environments. This chapter looks at the evolution of the industrial design and illustrates its evolution as an increasingly interdisciplinary scientific field.

Chapter 3 – This chapter focuses on the methodology of this research. The main hypotheses and the conceptual framework are described in this chapter. As the framework of this research is related to the model of the Double Diamond Design Process, it is introduced by this chapter. In Chapter 3 the affiliated methodology is emphasized. Besides the reasons for the method bundle selection, descriptions of utilized methods used for analysis of the status quo are given.

1.5.2 Define

Chapter 4 – This chapter reveals the preliminary results and findings of the pilot analysis. It discusses opportunities and challenges of contemporary existing workplaces in the digitised industry. Within the pilot analysis, design criteria based on the results of this research's analysis phase are given.

1.5.3 Develop

Chapter 5 – Based on the results of the analysis phase, the subsequent part of Chapter 5 documents the process of the demonstrator development starting from the design concept to the implementation as a prototype within a laboratory set-up. To enable the analysis of the effectiveness of the design decisions related to cognitive strain, the objective evaluation method was developed and is presented within a section of Chapter 5. Finally, this chapter focuses on evaluating the design criteria by conducting a controlled preliminary verification experiment on the prototype.

1.5.4 Deliver

Chapter 6 – This chapter discusses the results and draws conclusions. It presents the main contributions, discusses the limitations of this research, and makes recommendations for future work.

The thesis outline includes analysis-, approach-, implementation-, and evaluation phases which refers to the methodology of this research work (see. 3.1 The Framework for Innovation). Figure 3 gives an illustrated guide of the structure.

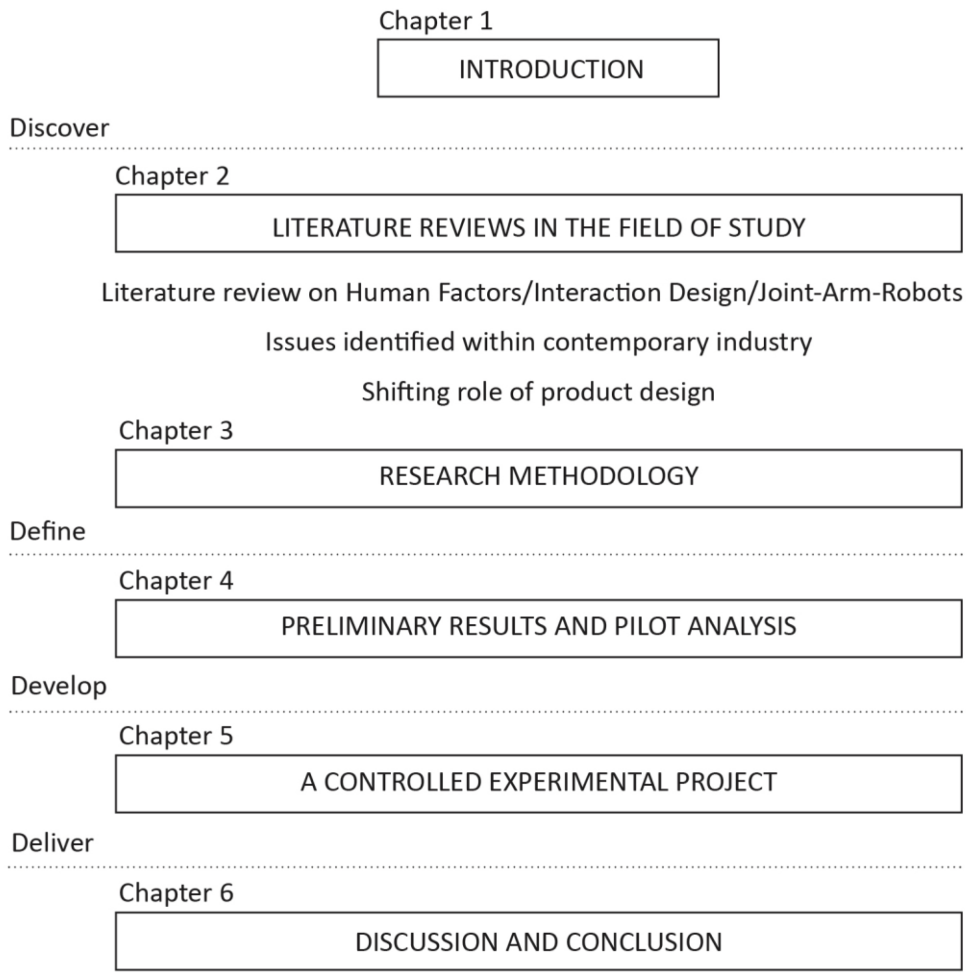

Figure 3 - Thesis structure and connection of each chapter to the methodology process.

1.6 Contributions of the Research

The main contribution of this research is to extend knowledge of workplace design focusing on HF by: (1) Developing reliable design criteria for workplaces of operators collaborating with robots; (2) An overall technique for evaluating the effectiveness of a design focussing on cognitive stress relief. This seamlessly combines techniques from interdisciplinary fields including: Engineering, Neuroscience, Gestalt theory, and Design. The design criteria and the evaluation methods developed can support professionals from various disciplines in the development of future system-designs by providing relevant indications of future human-centred investigations.

The thesis is adding the following contributions to the body of knowledge:

A. Knowledge in the field of HF related to the digitised industry and knowledge about how operators are influenced by working in collaboration with autonomously operating joint-arm-robots

B. Empirical analysis material of industrial field trips and expert insights of the researcher and professionals from the industry sector

C. Design criteria, theoretically and empirically based on the findings (B), to the relief of the strain of all three levels of HF dimensions

D. Development of a concept and construction of the prototype following the design criteria (C), based on an industrial scenario on a real-world case

E. Development of an objective evaluation method using an individual's brainwave frequency analysis by applying Machine Learning (ML)

F. Validation of the conceptual prototype (D) developed based on the design criteria (C) within a pilot study by user/acceptance tests using the evaluation method (E).

1.7 Summary of Chapter 1

This chapter described the background and motivation of this present thesis. It outlined the high number of potential issues industrial workplace environments exhibit, resulting from the high complexity of systems, the high dynamics from the integration of diverse communication devices, as well as the integration of autonomously acting machines, e.g. joint-arm-robots.

Accordingly, this chapter derived the research questions/aims and objectives of this research. Furthermore, this chapter illustrated this research's academic collaboration and its cooperation with industrial partners. This diverse alliance with representatives from academia, research institutes and industry results in a knowledge transfer over various disciplines investigating and developing the field of the digitised industry. Further, this chapter outlined this thesis structure. Finally, Chapter 1 clarified how this research contributes to the existing body of knowledge.

Chapter 2. Literature Reviews in the Field of Study

Starting from the technology-oriented point of view, the following chapter introduces the field of joint-arm-robots within the automated industry. Afterwards, this chapter takes the human-centred perspective and leads through the field of interaction design. Moreover, it discusses the three limitations of HF: the physical, cognitive and organisational ergonomics, to establish a background knowledge in the field of workplace design and its users. This chapter also discusses questions regarding issues within the existing digitised industry/workplace design for interaction with joint-arm-robots. Finally, this chapter derives how professional designer and engineers of the future should be educated to face those issues when developing workplace designs.

2.1 Joint-Arm-Robots within the automated Industry

This section seeks to giving an overview on current research work within robotics, in particular within the field of joint-arm-robots for HRC.

Niewerth et al. (2019) defines the term industrial robot as a flexible, movable machine with several axes. The movements of industrial robots are freely programmable in terms of sequence and path and, if necessary, sensor-controlled (Niewerth et al. 2019). Similarly, the IFR International Federation of Robotics (2020) uses the term industrial robot based on the ISO 8373:2012-03 - Robots and robotic devices - Vocabulary to describe an automatically controlled, reprogrammable multipurpose manipulator that is programmable in three or more axes.

A manipulator refers to the mechanical structure connected by axes that determines the kinematics of the robot. Literature distinct between industrial robots and service robots (Ben-Ari and Mondada 2018). Service robots are primarily used outside of the automated industry and are not considered in the further content of this research. Due to their specific structural characteristics, Automated Guided Vehicles (AGVs) are also excluded from the main consideration besides they can be equipped with a joint-arm-robot.

The ISO standard further classifies industrial robots according to mechanical structures into *cartesian robot*, *SCARA robot*, *articulated robot*, *parallel/delta robot*, and *cylindrical robot*

(ISO 8373:2012-03 - Robots and robotic devices - Vocabulary). Due to the importance of collaboration with operators for solving manual tasks, the main focus is on industrial articulated joint-arm robots.

Industrial joint-arm-robots can be equipped with tools and end-effectors to perform handling and manufacturing tasks. End-effectors can vary in shape and capabilities depending on the requirements of the task to be solved, e.g. gripper, measuring device, welding device et cetera. The design of the end-effector and the design of the robotic arm can be related to anthropometrics (FESTO 2017) or biomimetics (Xie et al. 2020), e.g. octopus and even can be built from soft material, e.g. soft robotic (Trimmer 2013).

The work area of a joint-arm-robot is called a cell and is physically secured by a fence or sensor systems (Niewerth et al. 2019). Conventional robots in industry require protective fences and other safety precautions. However, an innovative type of industrial robot was developed that allows the cooperation of operators with the machine within a shared, fenceless environment.

Cobots – articulated industrial joint-arm-robots for cooperation and collaboration

The new generation of robots: *'cobots'* are lightweight and equipped with sensitive sensors gently assisting the operator in a manual task as a *'3rd hand'* or *'helping hand'*. As KUKA AG (2021a) puts it:

'Cobots are collaborative robots that are allowed to work with people in the same work area without protective devices. Sensors and cameras on the cobot guarantee that the robot never injures its human colleagues.'

These are used in the automation of small-scale assembly tasks but also in the medical field, e.g. the LBR Med robot produced by KUKA mobilizes patients (KUKA AG 2021b). An overview of experiences and current research findings towards lightweight robotics in manual assembly gives Bauer et al. (2016). A description of the evolution of joint-arm-robots gives Moran (2007).

Products on the joint-arm-robot market differ in their repeatability, i.e. accuracy with which a robot can approach a point again, and in their handling weight. A selection of relevant products within the cobot market is given in table 1.

Table 1 – Market review. Articulated Cobots-producing companies.

Overview – selection of companies within the production sector of articulated Cobots

Product	Manufacturer	Number of axis
LBR iiwa	KUKA	Seven-axis

TX2touch	Stäubli	Six-axis
XCR20-1100	Siasun	Six-axis
MOTOMAN HC20DT	Yaskawa	Six-axis
YuMi	ABB	Six-axis
i-series	AUBO	Six-axis
Sawyer	rethink robotics	Seven-axis
TM series	TECHMAN	Six-axis
CR series	FANUC	Six-axis
Panda	Franka Emika	Seven-axis
UR series	Universal Robots	Six-axis

Computational models for programming the robots path planning/control of the robotic arm is a stand-alone field of research which will not be further regarded within this present thesis. A systematic review of current and emergent manipulator control approaches gives Ajwad et al. (2015).

To improve safe HMI with joint-arm-robots researcher are investigating power and force limitations of the robotic system (Aivaliotis et al. 2019; Vick et al. 2013). Furthermore, methods for monitoring workspaces for safe joint action for humans and industrial robots for assembly tasks are investigated by several researchers (Lenz et al. 2008 - 2008; Fraunhofer IFF 2016b). The findings of research are incorporated into standards and regulations. Specific safety-relevant standards regarding shared workplaces of Human-Robot Teams are listed in Section 2.3.1.

In sum, existing research in robotics largely focussing on the technology-oriented possibilities towards a safe interaction of humans with a robot. A growing part of research on robotics deals with interaction interfaces and introduced in Section 2.2.

Since this present thesis seeks to develop a theoretical design framework to support the interaction of humans and joint-arm-robots, the following section establishes a background knowledge within the field of interaction design.

2.2 Interaction Design

'Interaction Design is the creation of a dialogue between a person and a product, service, or a system.' (Kolko and Connors 2010)

To improve interactions between humans and machines, considerable attention must be paid to the design of interfaces. Interfaces are not only limited to Graphical User Interfaces (GUI) but also include objects that give content through form, material, haptic et cetera. Consequently, even a design decision concerning the material of a table surface can be seen as part of the Interface Design, as it delivers haptic information to the operator.

A classification of Interface Design gives (Blauhut 2015). Blauhut classifies two fields of interfaces:

1) Product-Interface
   - Product design
   - Industrial design
   - Design engineering
2) Graphical Interface
   - Web/Screen design
   - Graphic design
   - Software design
3) According to Blauhut (2015) both areas of Interface Design are incorporating Interaction Design.

In summary, Interaction Design focuses on the design of human activities, while Interface Design focuses on physical and graphical elements that are necessary for the success of such interactive activities (Blauhut 2015).

A broad field in research is investigating Interface Design for the human-computer-interaction/HMI. A view to selected areas that contributed to human-computer-interaction give Ebert et al. (2012). Interfaces for HRC are a specialised area of this field of research.

Besides the interaction via mouse and keyboard to manipulate the CPS, additional approaches can be declared. An overview of the HRC interfaces and interaction modalities, e.g. vision, audit, force/pressure, tactile feedback and bio-signals gives Ajoudani et al. (2018). A promising multimodal interaction interface for the control of robots by the operator's gaze has been developed by (Blume 2014). Moreover, sensitive robots enable the interaction of the CPS with the operator through physical contact rather than using screens (Acatech 2016).

Further investigations seek for alternatives to screens for providing information, e.g. instructions for the operator or status of machines. Some approaches use projection-based interfaces to display information for the operator, e.g. dimensions of movements of joint-arm-robots (Fraunhofer IFF 2016b, 2017). Moreover, there is an intersection for the visualization of instructions for manual task solving within the industry. Researchers develop the integration of guidance lights and projections within the workplace environment to instruct the operator (Bannat 2014; AiF Projekt GmbH 2018). Another approach focuses on the integration of screens or wearables to support the interaction with the CPS (Ziegler 2016).

HMI and corresponding interfaces show accelerated development. Since the introducing of autonomously operating machines, e.g. joint-arm-robots to the industry, interaction is becoming more complex. Consequently, Interaction Design seeks to develop assisting systems to reduce strain of the operator. The ability of the system to adapt to specific/individual needs/preferences of the operator is one approach of a rising field of research. Nowadays, experts draw attention to machines which are able to increasingly adapt to individual abilities and needs of the operator (German Federal Ministry of Labour and Social Affairs 2017; Acatech 2016). Accordingly, self-learning algorithms process large amounts of data and use these to adapt the system to changing conditions (Kunert et al. 2020).

To be able to design HMI, precisely the interaction with joint-arm-robots, this present research applies knowledge from the field of HFE. HFE aims to apply psychological and physiological principles while designing products, processes and systems to reduce human error and improve human interaction instead (Lee et al. 2017). The following section introduces the field of HFE and its three levels of HFE that are essential for the design of workplaces for operators working collaboratively with joint-arm-robots.

2.3 The Scope and Definitions of Human Factors and its Applications

Lee et al. (2017) declare safety, performance and satisfaction as the three main goals of HFE. Figure 4 illustrates primary application areas and their specific influence of the main goals. In workplace environments, the value of satisfaction unfortunately often suffers for the purpose of safety and performance. However, more balance between the three factors can be observed within high-risk domains. The most relevant factor in consumer products relies on satisfaction during usage of the product. Furthermore, Lee et al. (2017) highlight the importance to adjust the priority on the particular area of application but also consider that all goals can be achieved simultaneously due to good HF design.

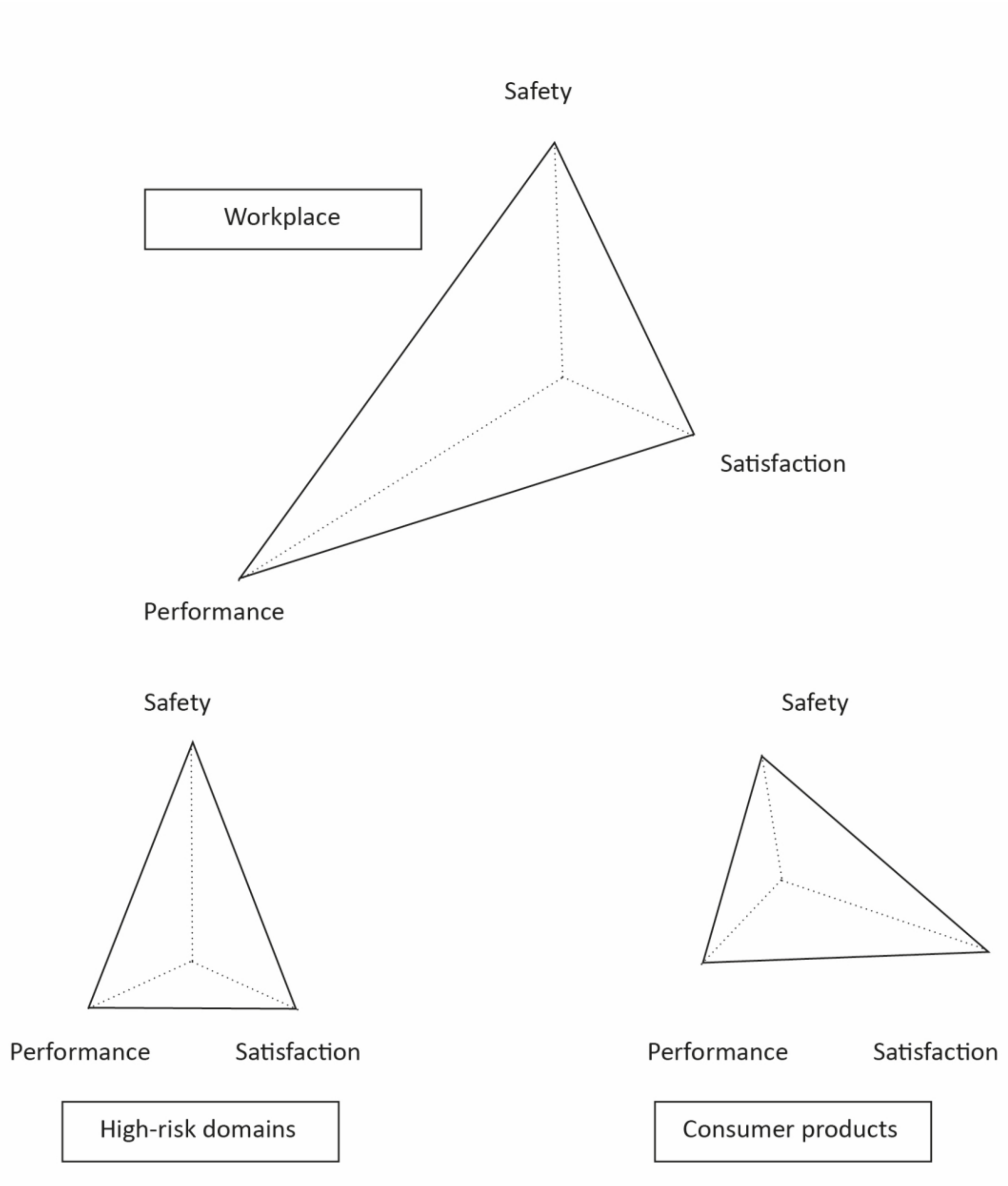

Figure 4 - Goals of HFE. The lengths of the lines mark the relevance within the system. Adapted from: Lee et al. (2017). No Creative Commons Licence.

Technical and HF design[9], both are important to the success of the automated systems. Furthermore, HRC can only be successfully integrated into the industrial production process, if user acceptance is certain. A growing body of literature describes the importance of understanding HF to assist the operator within the industrial workplaces (Lee et al. 2017). Some preliminary work was carried out in the early 1980s. Inter alia, Bainbridge (1983)

[9] HF design (or HFE) is defined by Lee (2017) as follows: HFE is a discipline that considers the cognitive, physical, and organisational influences on human behaviour to improve human interaction with products and processes.

already has mentioned the irony that the more advanced a control system is, so the more crucial may be the contribution of the human operator. Consequently, the study places great emphasis on the understanding of HF in terms of its physical, cognitive and organisational limitations and their applications to industrial design.

Concerning safety and performance within workplace design, HF must be supported in order to reduce the potential for unintended failure. There are many definitions of the term human error. In common they describe how human error refers to failure unintentionally undertaken through HF that may lead to an undesired outcome.

‘Error will be taken as a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to some chance agency.’ (Reason 1990)

Human error repeatedly occurs caused by poor system-designs based on a misunderstanding of human needs (Norman 1982). Adequate, human-centred product design concerns a deep understanding of HF (Norman 2013). Consequently, design decisions must regard not only the physiological but also the cognitive and organisational level of human needs (Lee et al. 2017). Vajna (2014) underlines the need for a holistic product development concerning all aspects of all three levels of HF. Accordingly, the connection of technical, ergonomic and aesthetic product quality is postulated for industrial design solutions by Rams (2014). The IEA gives a graphical overview of the relevant elements of HFE (see Figure 5).

Figure 5 - Three Levels of HFE and affiliated elements. Adapted from: International Ergonomics Association (2020).

The following section will introduce the three levels of HFE concerning workplace design and will give an insight into how industry and science apply knowledge in the field.

2.3.1 Physiological Limitations

An ergonomically correct designed workplace is a prerequisite for the human and economic use of human resources (Bullinger 1994). Ergonomics uses anthropometrical data to give a dimensional framework for the design of workplaces. Kamusella (2018) classifies two subcategories within anthropometrics:

- Body dimensions
- Body movement measures.

Figure 6 illustrates the classification by Kamusella (2018) and gives relevant information sorted in subcategories.

Those measurements are recorded statistically. Furthermore, demographic data such as age, gender, and origin have to be considered for the construction of workplaces.

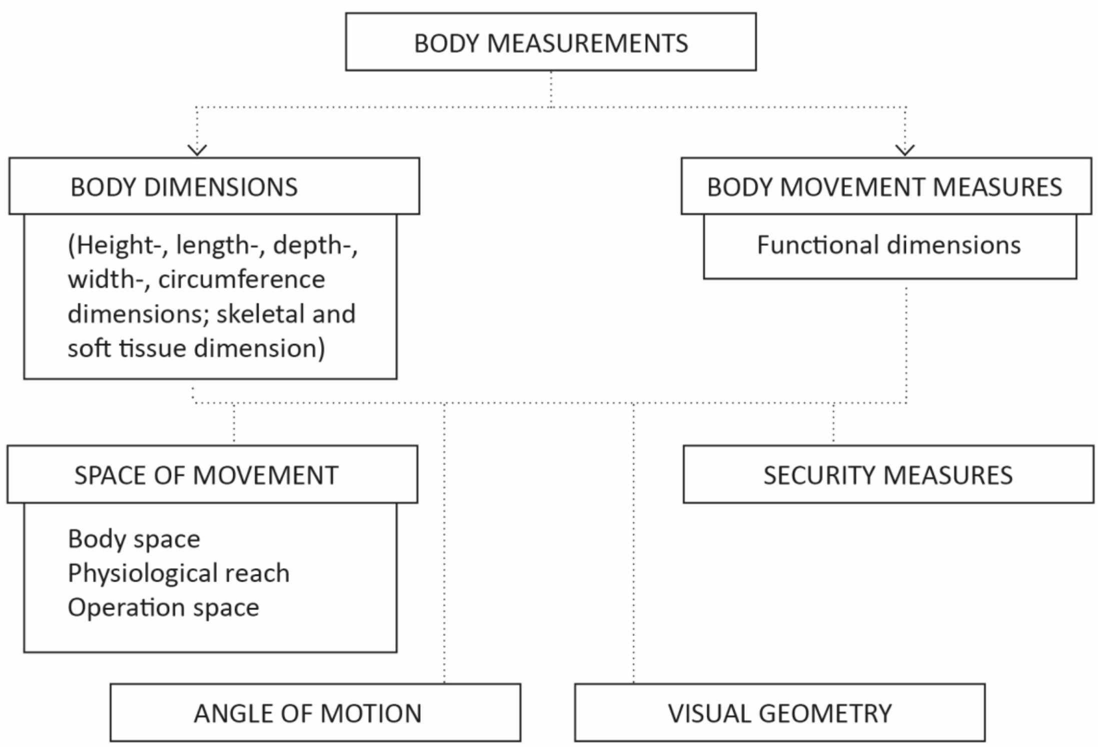

Figure 6 - Classification of physiological aspects. Adapted from: Kamusella (2018).

Knowledge of physiological limitations is important to deal with the optimal design of workplace systems and adaptation of working conditions to the operator needs. This includes the ergonomic principles of working height, foot room, the field of view and ease of reach. In excerpts, some major requirements from the design of workplaces concerning the ergonomic necessities of HMI are named below and reference is made to corresponding literature.

Mobility ergonomics

Using the average body dimensions of the population groups is not appropriate when designing workplaces. Therefore, the standard is the usage of upper and lower limits summarized under the term *'percentile'*. By using the 5th percentile of women and the 95th percentile of men as minimum or maximum limit, in summary, 90% of the population is considered. Figure 7 shows the variation of a measurement, e.g. body height of men in Germany in mm. It clearly illustrates that ergonomically system design must consider a difference of at least 205 mm for the adult male population in Germany. Consequently, the consideration of gender-based differences has to be considered within systems equally, usually, system designs orienting on W5 and M95 to serve both genders equally.

Figure 7 - Width of variation: body height in millimetre of adult men in Germany. Adapted from: DIN 33402-2.

To guarantee freedom of movement under the surface of tables for legs, knees and feet, the dimensioning of table systems is based on the dimensions concerning the W5 and M95 percentile. The dimensions of the workplace are designed for three different workplace types:

- Seating workplace

- Standing workplace
- Combined workplace for standing and sitting.

The choice of the appropriate system is justified by the requirement for the same.

Permanent sitting is life-shortening (Rezende et al. 2016). Therefore, the design of the work environment should enable the operator to change positions during the day. Ideally, the operator should switch between sitting and standing positions multiple times throughout the workday.

The subdivision of the percentiles as a guideline for the design of the workplace dimensions is, however, not completely sufficient, since each person has individual dimensions of the limbs. The literature here describes diverse types of body dimensions. Figure 8 illustrates the comparison of types where leg and trunk length are unevenly proportioned to an evenly promoted person. This means that people with a high overall body height due to a long upper body need a different adaptation of the work equipment from that for a person with a short upper body and high overall length due to long legs.

Figure 8 - Comparison of body types, unevenly proportioned leg and trunk length to evenly proportioned length. Adapted from: DIN 33402-2.

Even within a group of people who show similarity in terms of one or more body measurements, other measurements can be extremely different.

Since the range of the physiological reach varies due to the dimensional differences, those measurements have to be considered separately, Figure 9 shows how the anthropometric spaces for gripping and operating vary between the percentile W5 and M95. The area enclosed by a dotted line is the area that the operator can reach. The zone that is commonly used for the execution of manual tasks is highlighted in grey, the operating area. In terms of workplace design, this means that if people with different percentiles or body dimensions are sharing the same workplace with no adjustments regarding their specific requirements, this would have negative impact on the health of the affected people.

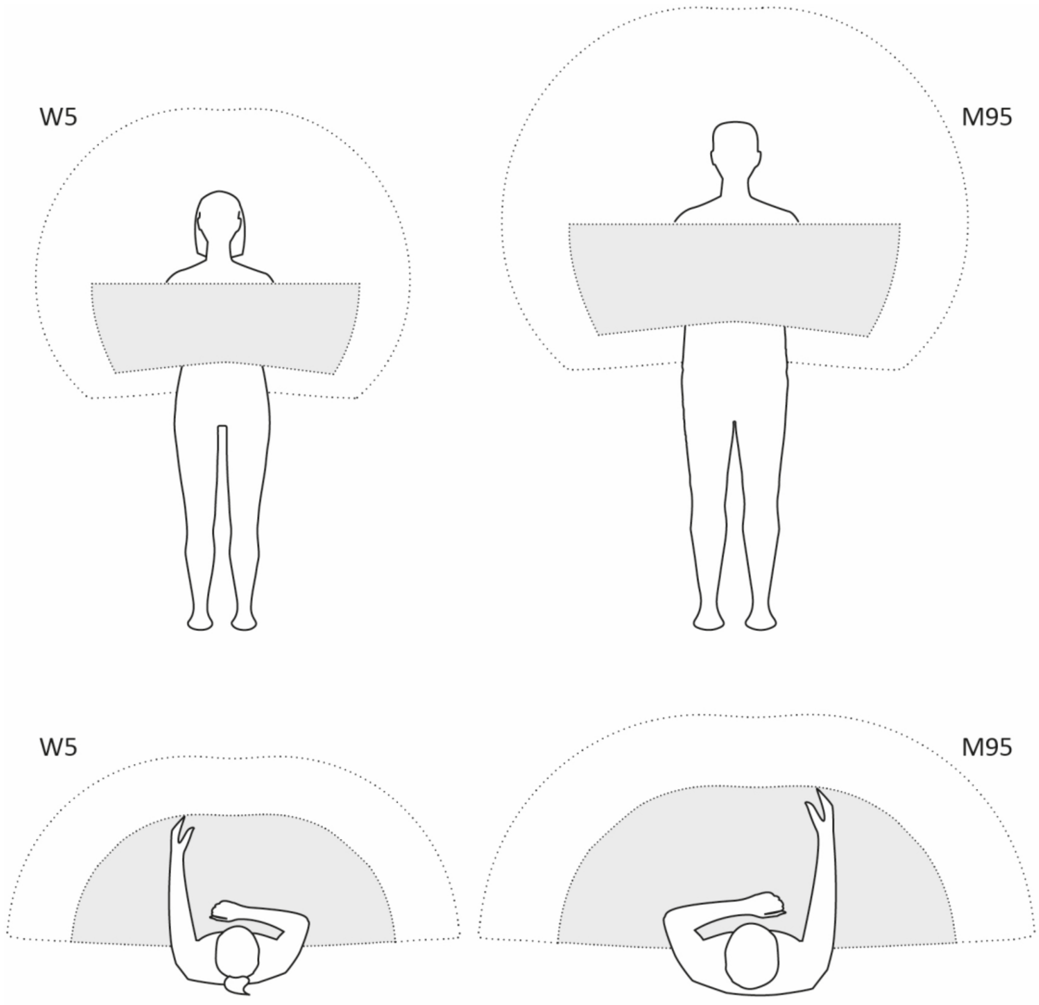

Figure 9 - Comparison of dimensions for gripping and operating between W5 and M95.

This applies especially when a workplace is shared within shifts. A step-less height and positioning adjustment of equipment components enable adaptation to the dimensions and requirements of various users.

Somatography is an instrument for a simplified description of anthropometrical models that can be used for the conception and design according to ergonomic requirements and targets. Examples of the analogue somatographies of human models are Kieler Doll (Jürgens et al. 1975) and the Bosch model (Jenner et al. 1978). Based on digital models, computer somatographies simulate the attributes of humans, e.g. Ramsis (Seidl 1997) and Jack (Badler 1993).

Virtual human models can also be immersively experienced by being displayed in so-called cave projections or via portable head-mounted display devices and used to analyse workplace design. Furthermore, digital somatography models can be also utilized to simulate the visual ergonomics for workplace design described within the following subsection. The IFE Institute for Energy Technology, a Norwegian research institute, developed the simulation software HVRC CREATE – by usage, the requirements for the holistic anthropometric design can be digitally simulated within a digital workplace environment to support the workflow (Louka et al. 2006).

Visual ergonomics

The *'range of vision'* describes the area of visual perception without movement of the body, e.g. the head (DIN EN ISO 14738).

According to DIN EN ISO 11064-4, the design guidelines for display elements relate to the positions of the user's visual axis, which in turn depends on the body size of the user group and the changing body posture when performing tasks at the workplace. The values of the inclination of the normal visual axis when sitting are given as an example: Within a sitting posture, the normal visual axis is directed straight ahead following the horizontal plane and lowered in the vertical plane by approximately 15 °to the horizontal axis. Different postures affect the position of the axis of the eyes as follows:

- Posture: bent over 20° ± 5°
- Posture: upright 30° ± 5°
- Posture: leaning back 15° ± 5°

In the horizontal deflection, the preferred visual space embraces an angle of ± 30°. For workplace designs, an acceptable range of ± 65° is given for the positioning of operation devices or interaction areas (Berufsverband der Augenärzte Deutschlands e.V. and Deutsche Ophthalmologische Gesellschaft 2007). Figure 10 illustrates the dimensions of vision ranges. Observation of objects and perception of warning signals can be optimally detected in this area.

Figure 10 - Range of vision a) accepted area b) preferred area. Adapted from: Berufsverband der Augenärzte Deutschlands e.V. and Deutsche Ophthalmologische Gesellschaft (2007).

Besides the anthropometrical dimension, external factors such as adequate illumination must be regarded. Prevention efforts also include the correct lighting of the workplace environment. In his book on product and workspace design, Bullinger (1994) gives recommendations for workplace design. The ten instructions for correct lighting include, among other things, a sufficiently high and harmonious level of brightness and the greatest possible glare limitation. The recommendations are used as a guideline for workplaces with integrated interaction devices. According to Bullinger the following reflectance limits in percentages have to be considered for material selection:

- Ceiling 70-90 %
- Table surface 20 -50 %
- Walls 40 -70 %
- Floor 15-35 %

Reflections cause severe irritation to the eyes, lead to eye fatigue and consequently should be avoided.

Particular attention should be paid to the use of bright projections on table surfaces within the work area of the operator. The contrasts that result from the need to ensure the perception of the projected content are extremely problematic regarding the reflection limits mentioned above. Furthermore, some irritations arise when projecting onto the operator's hands and arms. Also, the projection can be inevitably fragmented while working. The recording and interpretation of content and information of the projected information are thus disturbed. In particular, the use of such User Interfaces (UI) in the industrial environment finds another obstacle due to dust or smoke pollution.

In addition to the ergonomic requirements named above, the effect of environmental factors such as noise, illumination, climate or vibrations has to be considered, when designing workplaces (Alluisi and Morgan 1976). These factors are not discussed further in this work. A comprehensive overview of ergonomic factors is given by Bullinger (1994), Bullinger-Hoffmann and Mühlstedt (2016). Furthermore, a holistic overview of ergonomic requirements can be derived from the list of relevant standards given within the following section.

Standards on ergonomic requirements for workplace design

Kamusella (2018) divides the existing sources of ergonomic requirements into the following three categories.

A) Generally accepted rules of technology

This category includes existing formal regulations such as laws, standards and technical rules, e.g. DIN- and ISO- standards, national guidelines given in Germany for example by the VDE Association for Electrical, Electronic & Information Technologies or given by the VDI The Association of German Engineers and guidelines given by the Federal Ministry of Labour and Social Affairs.

B) State of the art

The state-of-the-art standards include general ergonomic knowledge that has proven itself by practical suitability, e.g. company-specific regulations.

C) State of scientific knowledge

Publications in professional journals or scientifically validated publications of national organisations like the German Federal Institute for Occupational Safety and Health are mentioned as an example for this category.

Frequently, more than one standard is used in the design and development process of workplaces in parallel. This is to be determined following the catalogue of requirements, including, for example, the work order, the target group, the work environment and equipment. Usually, a standard is related to several categories named above. The most important standards related to the workplace design of hybrid human-robot workplaces are listed within the following.

Standards for ergonomic workplace design for hybrid Human-Robot Teams

There is a considerable number of international standards focusing on the adequate design of workplace environments given by the International Standards Organization (ISO). Figure 11 gives an overview of groups of standards related to workplace design, which have been identified as relevant and which are presented within the following.

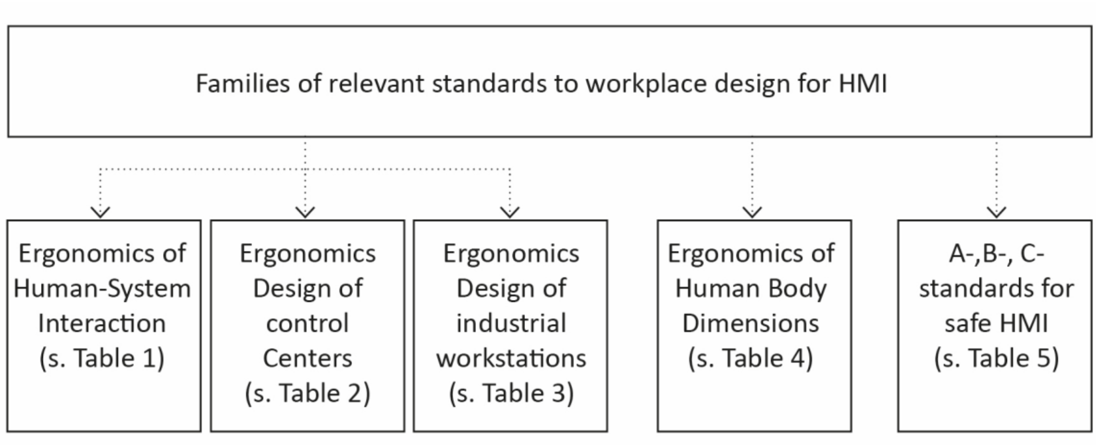

Figure 11 - Relevant groups of standards related to ergonomic workplace design.

The ISO 9241 has been describing quality guidelines for ensuring the ergonomics of interactive systems since 2006 under the heading 'Ergonomics of human-system interaction'. This guideline replaces the title 'Ergonomic requirements for office work with visual display terminals to remove the previous restriction to office work.

Information on current, relevant requirements for the design of workplace equipment and environments for hybrid Human-Robot Teams can be found in the following list of sub-standards affiliated to ISO 9241.

Table 2 - List of relevant standards concerning ergonomics of human-system interaction.

Ergonomics of Human-System Interaction	
DIN CEN ISO/TR 9241-331	Ergonomics of human-system interaction – Part 331: Optical characteristics of autostereoscopic displays (ISO/TR 9241-331:2012); German version CEN ISO/TR 9241-331:2013
DIN CEN ISO/TS 9241-411	Ergonomics of human-system interaction – Part 411: Evaluation methods for the design of physical input devices (ISO/TS 9241-411:2012); German version EN ISO 9241-411:2014
DIN EN ISO 9241-1	Ergonomic requirements for office work with visual display terminals (VDTs) – Part 1: General introduction (ISO 9241-1:1997) (including amendment AMD 1:2001); German version EN ISO 9241-1:1997 + A1:2001

DIN EN ISO 9241-5	Ergonomic requirements for office work with visual display terminals (VDTs) – Part 5: Workstation layout and postural requirements (ISO 9241-5:1998): German version EN ISO 9241 -5:1999
DIN EN ISO 9241-6	Ergonomic requirements for office work with visual display terminals (VDTs) – Part 6: Guidance on the work environment (ISO 9241-6:1999); German version EN ISO 9241-6:1999
DIN EN ISO 9241-11	Ergonomics of human-system interaction – Part 11: Usability: Definitions and concepts (ISO 9241-11:2018); German version EN ISO 9241-11:2018
DIN EN ISO 9241-13	DIN EN ISO 9241-13 Ergonomic requirements for office work with visual display terminals (VDTs) – Part 13: User guidance (ISO 9241-13: 1998); German version EN ISO 9241-13:1998
DIN EN ISO 9241-14	Ergonomic requirements for office work with visual display terminals (VDTs) – Part 14: Menu dialogues (ISO 9241-14:1997); German version EN ISO 9241-14:1999
DIN EN ISO 9241-15	Ergonomic requirements for office work with visual display terminals (VDTs) – Part 15: Command dialogues (ISO 9241-15: 1997); German version EN ISO 9241-15: 1997
DIN EN ISO 9241-16	Ergonomic requirements for office work with visual display terminals (VDTs) – Part 16: Direct manipulation dialogues (ISO 9241-16:1999); German version EN ISO 9241-16:1999
DIN EN ISO 9241-20	Ergonomics of human-system interaction – Part 20: Accessibility guidelines for information/communication technology (ICT) equipment and services (ISO 9241-20:2008); German version EN ISO 9241-20:2009
DIN EN ISO 9241-110	Ergonomics of human-system interaction – Part 110: Dialogue principles (ISO 9241-110:2006); German version EN ISO 9241-110:2006
DIN EN ISO 9241-110	Ergonomics of human-system interaction – Part 110: Interaction principles (ISO/DIS 9241-110:2019); German and English version prEN ISO 9241-110:2019 Blueprint as a replacement for DIN EN ISO 9241-110:2008-09 named above.

DIN EN ISO 9241-112	Ergonomics of human-system interaction – Part 112: Principles for the presentation of information (ISO 9241-112:2017); German version EN ISO 9241-112:2017
DIN EN ISO 9241-125	Ergonomics of human-system interaction – Part 125: Guidance on visual presentation of information (ISO 9241-125:2017); German version EN ISO 9241-125:2017
DIN EN ISO 9241-129	Ergonomics of human-system interaction – Part 129: Guidance on software individualization (ISO 9241-129:2010); German version EN ISO 9241-129:2010
DIN EN ISO 9241-143	Ergonomics of human-system interaction – Part 143: Forms (ISO 9241-143:2012); German version EN ISO 9241-143:2012
DIN EN ISO 9241-151	Ergonomics of human-system interaction – Part 151: Guidance on World Wide Web user interfaces (ISO 9241-151:2008); German version EN ISO 9241-151:2008
DIN EN ISO 9241-154	Ergonomics of human-system interaction – Part 154: Interactive voice response (IVR) applications (ISO 9241-154:2013); German version EN ISO 9241-154:2013
DIN EN ISO 9241-161	Ergonomics of human-system interaction – Part 161: Guidance on visual user-interface elements (ISO 9241-161:2016); German version EN ISO 9241-161:2016
DIN EN ISO 9241-171	Ergonomics of human-system interaction – Part 171: Guidance on software accessibility (ISO 9241-171:2008); German version EN ISO 9241-171:2008
DIN EN ISO 9241-210[10]	Ergonomics of human-system interaction – Part 210: Human-centred design for interactive systems (ISO 9241-210:2019); German version EN ISO 9241-210:2019
DIN EN ISO 9241-220	Ergonomics of human-system interaction – Part 220: Processes for enabling, executing and assessing human-centred design within organizations (ISO 9241-220:2019); German version EN ISO 9241-220:2019

[10] Chapter 3 Research Methodology will elaborate on the relation of the methodological structure of this research work to DIN EN ISO 9241-210.

DIN EN ISO 9241-300	Ergonomics of human-system interaction – Part 300: Introduction to electronic visual display requirements (ISO 9241-300:2008); German version EN ISO 9241-300:2008
DIN EN ISO 9241-302	Ergonomics of human-system interaction – Part 302: Terminology for electronic visual displays (ISO 9241-302:2008); German version EN ISO 9241-302:2008
DIN EN ISO 9241-303	Ergonomics of human-system interaction – Part 303: Requirements for electronic visual displays (ISO 9241-303:2011); German version EN ISO 9241-303:2011
DIN EN ISO 9241-304	Ergonomics of human-system interaction – Part 304: User performance test methods for electronic visual displays (ISO 9241-304:2008); German version EN ISO 9241-304:2008
DIN EN ISO 9241-305	Ergonomics of human-system interaction – Part 305: Optical laboratory test methods for electronic visual displays (ISO 9241-305:2008); German version EN ISO 9241-305:2008
DIN EN ISO 9241-306	Ergonomics of human-system interaction – Part 306: Field assessment methods for electronic visual displays (ISO 9241-306:2018); German version EN ISO 9241-306:2018
DIN EN ISO 9241-307	Ergonomics of human-system interaction – Part 307: Analysis and compliance test methods for electronic visual displays (ISO 9241-307:2008); German version EN ISO 9241-307:2008
DIN EN ISO 9241-333	Ergonomics of human-system interaction – Part 333: Stereoscopic displays using glasses (ISO 9241-333:2017); German version EN ISO 9241-333:2017
DIN EN ISO 9241-391	Ergonomics of human-system interaction – Part 391: Requirements, analysis and compliance test methods for the reduction of photosensitive seizures (ISO 9241-391:2016); German version EN ISO 9241-391:2016
DIN EN ISO 9241-392	Ergonomics of human-system interaction – Part 392: Ergonomic recommendations for the reduction of visual fatigue from stereoscopic images (ISO 9241-392:2015); German version EN ISO 9241-392:2017
DIN EN ISO 9241-400	Ergonomics of human-system interaction – Part 400: Principles and requirements for physical input devices (ISO 9241-400:2007); German version EN ISO 9241-400:2007

DIN EN ISO 9241-410	Ergonomics of human-system interaction – Part 410: Design criteria for physical input devices (ISO 9241-410:2008 + Amd.1:2012); German version EN ISO 9241-410:2008 + A1:2012
DIN EN ISO 9241-420	Ergonomics of human-system interaction – Part 420: Selection of physical input devices (ISO 9241-420:2011); German version EN ISO 9241-420:2011
DIN EN ISO 9241-910	Ergonomics of human-system interaction – Part 910: Framework for tactile and haptic interaction (ISO 9241-910:2011); German version EN ISO 9241-910:2011
DIN EN ISO 9241-920	Ergonomics of human-system interaction – Part 920: Guidance on tactile and haptic interactions (ISO 9241-920:2009); German version EN ISO 9241-920:2016
DIN EN ISO 9241-960	Ergonomics of human-system interaction –Part 960: Framework and guidance for gesture interactions (ISO 9241-960:2017); German version EN ISO 9241-960:2017
DIN ISO/TR 9241-100	Ergonomics of human-system interaction –Part 100: Introduction to standards related to software ergonomics (ISO/TR 9241-100:2010)

As part of the series DIN EN ISO 9241 Ergonomics of Human-System Interaction the following standard provides guidelines related to assistive systems:

DIN 92419:2020	Principles of the ergonomic design of assistive systems

Furthermore, ISO 11064 bundles aspects affiliated with the design of ergonomic design of control centres and principles for the development of adequate work environments within safety-critical or hazardous environments are covered. Many of the established ergonomic principles are relevant and applicable to the design of workplaces for HRC and therefore given within the following list.

Table 3 - List of relevant standards concerning the ergonomic design of control room centres.

Ergonomic design of control centres	
DIN EN ISO 11064-1	Ergonomic design of control centres – Part 1: Principles for the design of control centres (ISO 11064-1:2000); German version EN ISO 11064-1:2000

DIN EN ISO 11064-2	Ergonomic design of control centres — Part 2: Principles for the arrangement of control suites (ISO 11064-2:2000); German version EN ISO 11064-2:2000
DIN EN ISO 11064-3	Ergonomic design of control centres –Part 3: Control room layout (ISO 11064-3:1999) Correction to DIN EN ISO 11064-3:2000-09 (EN ISO 11064-3:1999/AC:2002)
DIN EN ISO 11064-4	Ergonomic design of control centres –Part 4: Layout and dimensions of workstations (ISO 11064-4:2013); German version EN ISO 11064-4:2013
DIN EN ISO 11064-5	Ergonomic design of control centres – Part 5: Displays and controls (ISO 11064-5:2008); German version EN ISO 11064-5:2008
DIN EN ISO 11064-6	Ergonomic design of control centres –Part 6: Environmental requirements for control centres (ISO 11064-6:2005); German version EN ISO 11064-6:2005
DIN EN ISO 11064-7	Ergonomic design of control centres –Part 7: Principles for the evaluation of control centres (ISO 11064-7:2006); German version ISO 11064-7:2006 Correction to DIN EN ISO 11064-7:2006-08

Table 4 - List of relevant standards concerning the ergonomic design of workstations placed near machinery.

Ergonomic design of industrial workstations	
DIN EN ISO 14738	Safety of machinery – Anthropometric requirements for the design of workstations at machinery (ISO 14738:2002 + Cor. 1:2003 + Cor. 2:2005); German version EN ISO 14738:2008
DIN EN ISO 14738	Safety of machinery –Anthropometric requirements for the design of workstations for industries and services (ISO/DIS 14738:2020); German and English version prEN ISO 14738:2020

For the development of workplace dimensions, the following standards deliver values of human body dimensions and give principles for selecting and using test persons.

Table 5 - List of standards concerning values of general ergonomics of human body dimensions.

Ergonomics of human body dimensions

DIN 33402-2	Ergonomics - Human body dimensions
DIN EN ISO 15537	Principles for selecting and using test persons for testing anthropometric aspects of industrial products and designs (ISO 15537:2004); German version EN ISO 15537:2004

When designing workplaces for HMI, the security-relevant standards that regulate the interaction must be taken particularly into account. The relevant safety-related standards in Europe are classified into three subcategories, e.g. A-, B-, and C-standards. Fraunhofer Austria & TÜV AUSTRIA Gruppe (2016) gives a structural graphical overview (see Figure 12).

A-, B, C-standards are grouped according to their hierarchical meaning. Standards within the group A describing procedures for risk assessment and risk reduction related to machinery in general. B standards describe general safety-related design aspects that are relevant for numerous machines. Moreover, C standards are highly machine-specific and deal with procedures to reduce risks associated with these special machines and related systems. Furthermore, robot-specific standards, especially for HRC, have been addressed within standards. Those standards are highly machine-specific and therefore are included within the group C.

Figure 12 - Relevant standards from the perspective of an HRC application (extract). Adapted from: Fraunhofer Austria & TÜV AUSTRIA Gruppe (2016).

Table 6 - DIN standards – affiliated with safe HMI.

A-, B-, C-standard for safe HMI

A-standard

DIN EN ISO 12100	Safety of machinery –General principles for design –Risk assessment and risk reduction (ISO 12100:2010); German version EN ISO 12100:2010, Corrigendum to DIN EN ISO 12100:2011-03

B-standard

DIN EN ISO 13849	Safety of machinery –Safety-related parts of control systems

DIN EN 62061	Safety of machinery - Functional safety of safety-related electrical, electronic and programmable electronic control systems

C-standard

DIN EN ISO 10218-1	Robotics –Safety requirements for robot systems in an industrial environment – Part 1: Robots (ISO/DIS 10218-1:2020); German and English version prEN ISO 10218-1:2020
DIN EN ISO 10218-2	Robots and robotic devices –Safety requirements for industrial robots – Part 2: Robot systems and integration (ISO 10218-2:2011); German version EN ISO 10218-2:2011
DIN EN ISO 11161	Safety of machinery –Integrated manufacturing systems – Basic requirements (ISO 11161:2007 + Amd 1:2010); German version EN ISO 11161:2007 + A1:2010
DIN ISO/TS 15066	Robots and robotic devices –Collaborative robots (ISO/TS 15066:2016)

These lists are not intended to be exhaustive. All actors of a CPS including robots have to undergo a risk assessment when operating separately and similarly considered when connected within an interacting system. Specifically, for the appropriate application, the standards must be considered for their applicability and, if necessary, supplemented with other standards. In addition, the further development of the standards especially regarding collaboration with robots is characterized by a high dynamic. Therefore, the current state of the standards must be regarded.

In addition to the DIN EN ISO standards, reference is made to the work of REFA Bundesverband e.V (2020). A major methodology considering ergonomic aspects is given by the REFA focus on optimising work processes and increasing productivity. REFA is Germany’s oldest organisation for work design, company organisation and corporate development and develops methods for applications within the industrial field and service sector. The methodology can be applied in many scientific fields and professional industrial applications such as industrial engineering and design, business administration, health management etc.

The literature points out that the system design not only needs to consider the ergonomic requirements but also needs to consider psychological aspects to support the user, e.g. operator (Bullinger-Hoffmann and Mühlstedt 2016; Vajna 2014; Bauernhansl et al. 2014). Within the following section, the cognitive limitations of the operator within the design process of workplace systems are described to define the needs of the operator.

2.3.2 Cognitive Ergonomics

Psychological influences while working in an industrial environment affect the operator. This section discusses insights on a review of scientific material to give an understanding of the phenomena of cognitive processes concerning human behaviour. Furthermore, relevant psychological processes are described, which influence performance, health, and well-being by increasing the mental workload of the operator.

Increased mental workload due to the high dynamics of the industry

The higher dynamics of the processes within the industry requests a permanent interpretation of signals and adequate reactions of the operator. Similarly, Bauernhansl et al. (2014) draw attention to the flood of data resulting from global networking and ever-improving device technology and concludes that the support of the operator in the production plant will become increasingly important. In the same way, the German Federal Ministry of Education and Research (2016) refers to the importance of assistance systems within a changing work environment and high dynamics of the industry.

Mental workload and stress

The increasing complexity of people's interaction with machine interfaces, as well as the rapid development of the technological framework, fundamentally changes the way tasks are handled and therefore the demands on the design of work environment and work equipment are changing. Mobile computing devices (wearables, virtual and augmented reality, interactive projections) expand beyond conventional communication channels. The processing and control of work orders are no longer exclusively via keyboard and computer mouse. Moreover, communication with the system becomes more multifaceted and complex by networking with machines and robots in the industry. Gorecky et al. (2014) use the term *'mental work'* to describe the main activity for operators within the I4.0 environment.

A general definition of the term *'mental workload'* is given by Kantowitz (1988) as follows: 'Mental workload as an intervening variable, similar to attention, that modulates the tuning between the demands of the environment and the capacity of the organism.'. Accordingly, Macdonald (2003) characterises the term *'mental workload'* as the perceived gap between the task demands and the motivated coping capacity of a person. In this line, Reisman (1997) defines the term *'stress'* as the body's reaction to a perceived mental, emotional or physical distress.

In this context, Kantowitz (2000) further explains that unsatisfactory operator performance will occur whenever there is a mismatch between environmental demands and operator capabilities. He highlights that the likelihood of human errors arises if the workload is too high or too low (Kantowitz 1988). This effect is described by several researchers as a result of the limitation of the human brain's ability to cope with information rates emitted by the environment and is discussed further within the following.

Limitations of perception

Working in an industrial environment, especially interacting with CPS, requires a steady reception and adequate interpretation of signals by the operator. To be able to create a supportive working environment the limitations of the human brains while processing visual information must be regarded.

Limitations of visual memory

The sense organs collect information about the environment. Targeted action requires that our brain can extract relevant information from the stream of signals that are related to the current important need for action. Endsley and Jones (2012) outlined how the human brain becomes a bottleneck when the design of work equipment does not provide support for rapid information processing. An adequate design promotes a rapid reception of information and supports the interpretation process so that this bottleneck is overcome. Figure 13 illustrates the dynamic of visual perception processes.

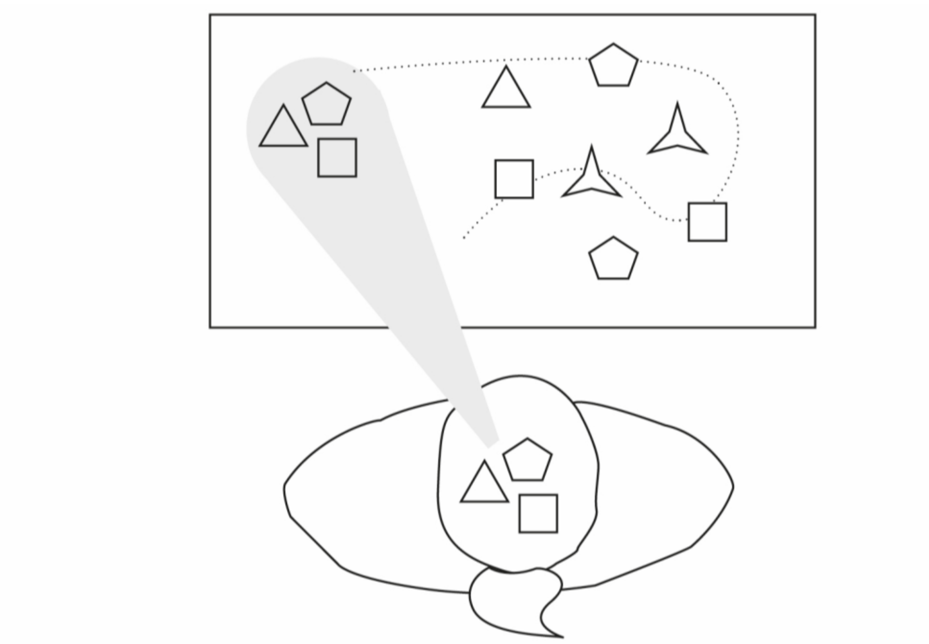

Figure 13 - Limitation of perception through the limited memory resource of the human brain. Adapted from: Braseth (2015). No Creative Commons Licence.

Braseth (2015) describes how after a fast scanning through a saccade cycle (dotted line), a rapid movement of the eye between fixation points, only a small area of the visual signals is processed afterwards because the visual memory of the brain is severely restricted. In the case of cognitive overload due to design rich in elements of different colours, shapes and movements, required information can be easily overlooked. Besides this critical selection effect, sensory impressions enter our brain after running through a filtering and evaluation process. The field of Gestalt theory deals with the processes of human perception. According to Gestalt theory, our environment is perceived through the perception of forms (Bühler et al. 2017).

Perception of forms according to Gestalt theory

Gestalt theory has formulated various laws on the organisation of perception, inter alia, the law of closeness - that elements placed close to each other are experienced as a group (see Figure 14). Accordingly, the elements that are separated are perceived as a related connection.

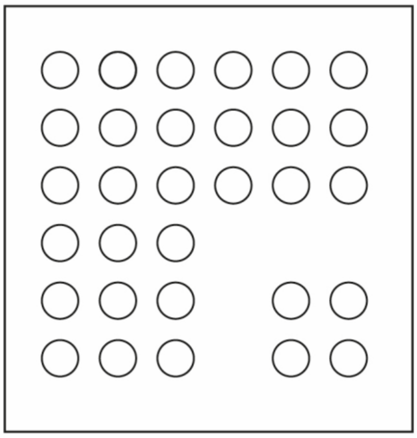

Figure 14 - Gestalt theory. Law of closeness. The four elements are perceived as a related group due to their closeness.

In addition, the law of equality is to mention as a further example (see Figure 15). This law describes that elements with the same attributes are recognized as a related group.

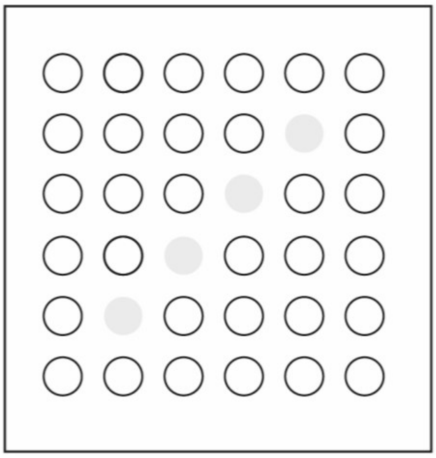

Figure 15 - Gestalt theory. Law of equality. The four elements are perceived as a related group due to the shared attribute equality of tonal value.

Masking effects

In the same context, Braseth (2015) described the problem of unfortunate masking effects which negatively influence the perception of important information. Figure 16 (left) illustrates how an object can be easily detected, if an attribute (here tonal value) differs from the other objects, also if the objects share the same shape. Conversely, on the visualization (see Figure 16, right) a masking effect occurs due to the addition of objects with the same tone value. Also, if they are characterized by a different shape, it needs a strong focus to identify the round, tone-value added circle. Those effects occur if irrelevant background signals are disturbing the viewer's attention. To overcome this problem the avoidance of competing elements is sought.

This is in line with Blauhut (2015) who describes how technologies overloaded with unnecessary features and properties are more complex and thus more difficult to understand, which can cause stress to the intended user.

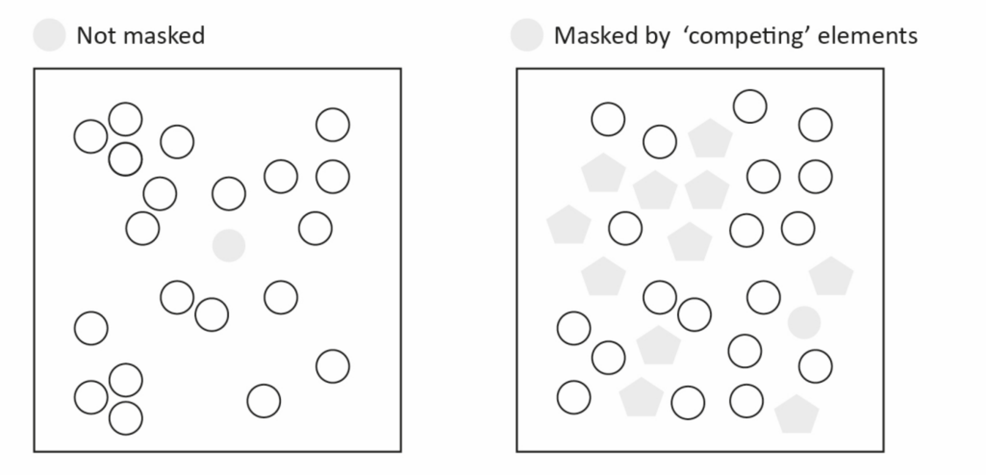

Figure 16 - Masking effect through 'competing' elements. Adapted from: Braseth (2015). No Creative Commons Licence.

Arousal

A major psychological principle was formulated in 1908 by the psychologists Yerkes and Dodson. Similarly, the Yerkes-Dodson law (Teigen 1994; Yerkes and Dodson 1908) describe the importance of an optimal level of arousal for solving tasks and underline that high arousal negatively affects the psychological ability to process visual information. Their study provides considerable insights into the negative effects on the well-being of the operator caused by the permanently high cognitive load coupled with generally higher dynamics of the process. This theory was previously based on an experiment with animals and later generalised to humans.

In its graphical representation, it describes an inverted U-shaped relationship between arousal and performance of an individual within the different levels of difficult tasks. Figure 17 illustrates that lower arousal, as well as over-excitation, are more likely to be associated with performance decrease but also illustrates how human performance depends on the complexity of the task and the mental activation. A high level of nervous stimulation significantly lowers performance in solving complex tasks (Goschke 2013/14).

Consequently, inadequate arousal leads to poorer performance and increased error rate, since relevant stimuli are also hidden for perception. The more complex the task, the more stimuli need to be considered. Accordingly, a lower arousal level is optimal for a high level of performance. Given the discussion above, optimal performance on different tasks requires a different level of arousal.

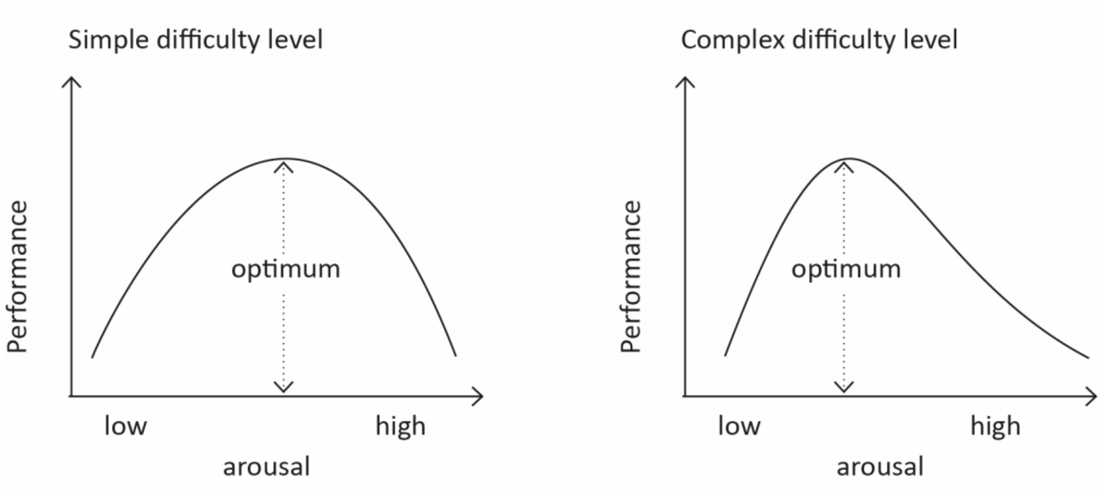

Figure 17 - Hebb/Yerkes-Dodson Hybrid. Adapted from: Teigen (1994). No Creative Commons Licence.

Based on the Yerkes-Dodson principle, a framework was advocated by Easterbrook (1959) which further explains that, in each situation, the attention of the individual is directed to some specific stimuli, while others are ignored. The level of activation affects how many stimuli get into the focus of attention. The higher the activation of the individual, the narrower the attention focus. This corresponds to the suggestion by Braseth (2015), who demonstrates how one of the main issues for designing visual interfaces is to avoid information overload. Furthermore, mental fatigue due to low arousal has to be carefully regarded as a crucial factor for human performance and must be considered when designing interaction systems (Bullinger 1994).

Besides cognitive perception influencing the work of operators, the individual's perceived acceptance towards the integration of CPS within the working environment is crucial.

Acceptance

The successful integration of CPS, e.g. HRC, results from acceptance of the operators towards them. To create an environment that relieves the operator, it has to be examined under what conditions they accept the work in direct interaction and collaboration with robots. In his investigations into the acceptance towards robots, Masahiro Mori (1970)[11] explored that the perception did not produce a steady increase in familiarity and acceptance with increasing degrees of human similarity. There are some approaches to integrate facial expressions to industrial joint-arm-robots, which showed increased acceptance due to the utilization of social cues (Elprama et al. 2016). However, it leads to irritation if the robot is too humanized in its general appearance according to Mori (1970) who introduced the term *'uncanny valley'* to describe that acceptance gap (see Figure 18).

[11] Japanese roboticist and researcher on human emotional responses to non-human beings.

Figure 18 - Uncanny Valley. Adapted from: Mori (1970).

Therefore, factors such as the radius of the reach of the robot, the influence of different velocities of movement and the general influence by external shape and colour must be investigated (Chandrasekar 2011). Furthermore, the CPS including the robot must meet the conformity of expectations of the user. This is a highly important element for increasing acceptance and therefore enables the successful integration of an interaction system.

Conformity with expectations

In her introduction into the field of Human-Machine Systems (HMS) Kamusella (2018) illustrates the connection of the actor *'human'* with the actor *'machine'* within a shared system as follows (see Figure 19).

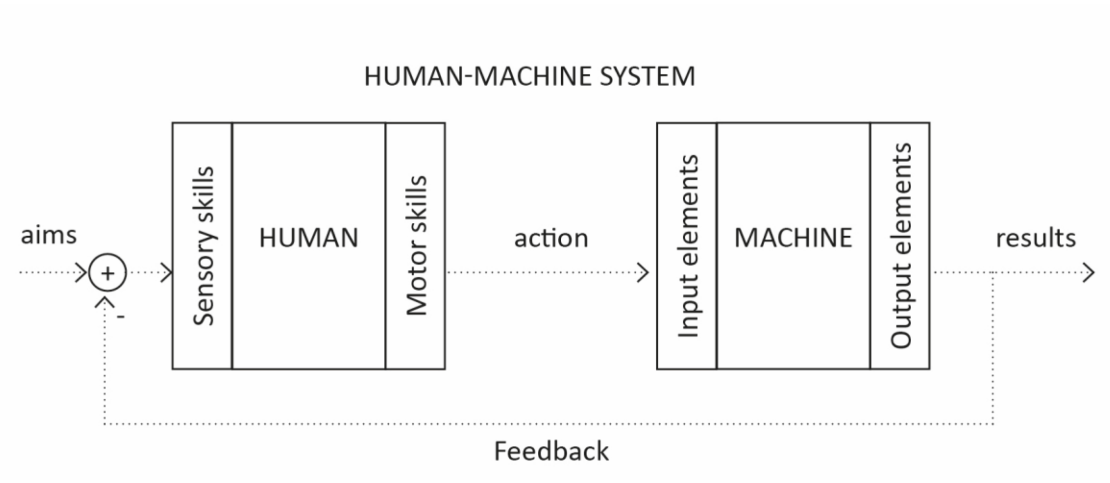

Figure 19 - Human-Machine System. Adapted from: Kamusella (2018).

Reactions of the system acting conform to the expectation of the user results in a positive experience which promotes acceptance towards the system. This principle was incorporated into DIN EN ISO 9241-110 - Ergonomics of human-system interaction –Part 110: Interaction principles; principles of dialogue design under the term *'expectancy confirmation'*.

An adequate workplace design takes rational aspects into account, but equally psychological aspects as the conformity with expectations must be considered, e.g. the perception of a robot colleague (Stark et al. 2018). Since autonomous robot movement rhythms are generally not predictable, there are still barriers in the HRC that causes stress. Some researchers are already trying to overcome this limitation by investigating solutions to indicate the status of the robot (Mobile Industrial Robots A/S 2019; Franka Emika GmbH 2020b) even via facial expressions (rethinkrobotics 2019), or light projections for dynamic work area monitoring of the robot (Fraunhofer IFF 2016a).

Some transportation robots, e.g. AGVs are using flashing signals or sounds[12] to indicate their future direction. However, at this moment a visual display to indicate the future direction of movement of industrial joint-arm-robots while interacting with humans solving manual tasks is widely missing. A promising investigation is currently being carried out by Sumona Sen, whose research aims to investigate a robot's path planning that allows generating a high degree of situational awareness through better conformity of expectations (Buxbaum 2020).

Cognitive environments

Due to the significance of cognitive load, a workplace system must be decluttered from unnecessary information. That means an environment should aim to be characterised by signals and information which are minimised to deliver only relevant information. Furthermore, features from traditional industrial design rules support the intuitive meaning assignment of physical and digital interaction objects. Given the discussion above, workplace systems should be seen as cognitive environments aiming to proactively support the operator. The Fraunhofer Institute for Industrial Engineering IAO uses the term *'cognitive environments'* to refer to a concept of an agile workplace environment, which can adapt to changing conditions to support in the best way possible the specific needs of the employee for task solving (Stolze 2019).

Cognitive environments are already merging cognitive ergonomics with the area of organisational applications of HF, which will be discussed within the following section.

[12] The utilization of sounds within an industrial environment shows issues, because due to the occurrence of high noise pollution the signals can be easily missed.

2.3.3 Organisational Applications

The digitalization is changing the character and organisation of work environments in the office, but also in the industry, as well as the character of work itself. Hackl et al. (2017) underline that in response to technological and economic volatility, the needs of employees within the *'New Work'*[13] have changed. Industry actuators are networked with one another and constantly exchange data. Therefore, organisational applications of HF are aiming to enable a structural organisational network, regarding all actors within this interaction system which is regarding the requirements HF needs.

Throughout this work, the terminology Human and Organisational Factors (HOF) will refer to the definition given by the European Union Agency for Railways (2020). The Agency describes HOF as the interactions among system components and humans, considering their behaviours, at all levels such as individual, situational, group, organisational or cultural.

The organisational applications of HF refer to *'macroergonomics'*[14] of a work-system. Kleiner (2006), gives a basic-work-system-model including the following factors:

- External environment
- Technical subsystem
- Personal subsystem
- Internal environment
- Organisational & managerial structure

These factors are to be considered within the design of the organisational architecture[15] of a company.

Leading forces on organisational applications of HF is shown in Figure 20. To understand HOF and their importance for the improvement of working conditions, the context and the relation to real-world processes have to be considered. Therefore, the three main drivers and their impacts on organisational applications of HF concerning industrial workplace design are explored within the following.

[13] The term *'New Work'*, according to Hackl et al. (2017), is still vaguely defined but stands for fundamental changes in the world of work due to disruptive societal and technological changes and the resulting upheavals at the corporate level.

[14] Kleiner (2008) defines *'macroergonomics'* as a sub-category of HF which refers to the study of work-systems that knowledge provides the organisational support for designing effective work-systems.

[15] Referring to Nadler and Tushman (1997) the organisational architecture describes the structure and organisation of work.

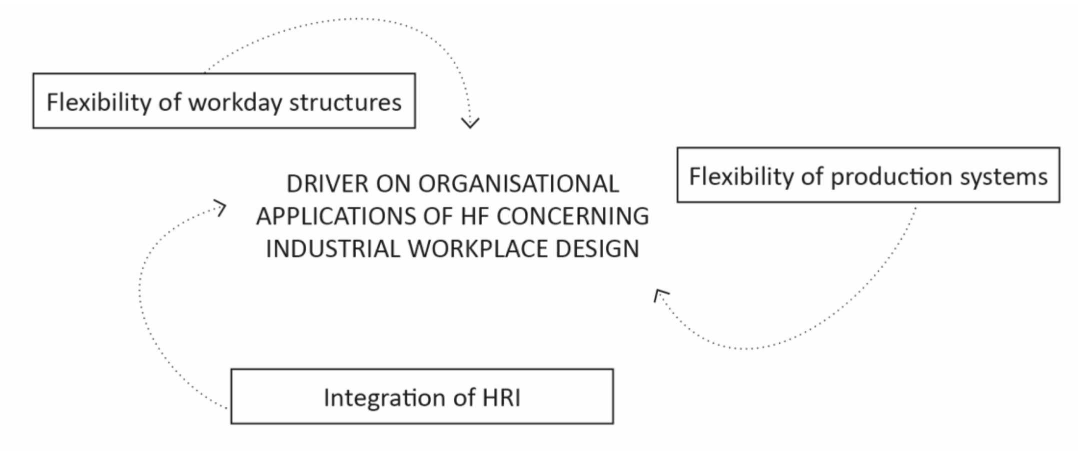

Figure 20 - Driver of the organisational applications of HF. Those drivers are influencing the requirements on workplace design.

The flexibility of workday structures

The office increasingly becomes a lively meeting place that leaves the separation of life and work behind, modern office architecture and design supporting the merging process by development of appropriate workplace structures.

Office architecture and office interior design

James Irvine´s vision of the *'citizen office'* appears like a living organism. In 1993 he had drawn an imaginary picture of his idea of how future offices should be organised like landscapes, characterised by customized zones for the individual need for every task within the workday (Figure 21).

Figure 21 - Citizen office diagram. Adapted from: James Irvine (Vitra AG 2014).

The citizen office is a complex, lively meeting place that is adapted to support a dynamic work life. Likewise, he has created the map connecting zones for focussed, enclosed mental work accompanied with open zones for meetings which are placed close to coffee-zones for a short break. The office, seen as an open landscape, is harmonizing the different needs of employees, which occur and change depending on the work task during the day.

Today, the company Vitra is transferring Irvine´s idea into modern office concepts. Vitra´s citizen office is located at the headquarters in Weil am Rhein and is based on Irvine's drawing. The office landscape is characterised by separation into diverse zones for quiet work, teamwork, meeting- and conference areas. Indeed, during a visit to the company's citizen office, Vitra showed that even small architectural or office organisational design decisions can succeed to release the strain of the operator, e.g. to integrate more movement into the daily work routine of employees. To illustrate, all workplaces are sharing central trash cans so the employee is kindly motivated to change posture during the day.

Moreover, Vitra also uses an open architecture structure to support communication. Coffee-stations are consciously placed near central walkways to allow random meetings between colleagues. Those areas are framed with standing workstations so opportunities are given to hold small meetings while enjoying a coffee.[16] Along with the organisational design decisions given above, no employee has a fixed workplace. Vitra enables their employees to move freely from one workplace to another, changing the environment according to the needs of the task which has to be solved. To enable this, the employee places their laptop at a free place and can connect to the system. Furthermore, employees are given the opportunity to store personal belongings at a central locker system consisting of mobile lockers.

Modern office structures offer maximum flexibility and mobility (Steelcase Inc. 2017b). Corresponding to the flexibilization of office work, flexible work-systems outside of the offices have heightened within the last years. Mobile forms of work like co-working[17], but also like crowd working, work-from-home, Flextime models etc. are describing a trend towards distributed, inter-organisational and collaborative knowledge (Spinuzzi 2012). The increased flexibilization of work is given as a major aspect of modern and future workplace design changes.

There is a particularly high potential in the transfer of these mobile work form concepts such as flexible, time and location-independent working hours to the industrial work environment.

New Work within Post-Corona Economy

The German National Stakeholder Platform I4.0 give ten propositions on the future of New Work in the digitised industry related to the consequences of the COVID-19 pandemic (Piller 2020). The author underlines that flexibility and agility become the basis of competitiveness. Specifically, the core design principle for the factory of the future will be assortment and volume flexibility, and new forms of organisational design need to be considered to answer physical distancing in production. The author points out the increasing importance of remote service, flexible work and flexible learning. As Piller (2020) puts it:

‘Former implementation barriers and adaptation hurdles for digital tools and processes have been drastically reduced – flexible trial-and-error experimentation has been rewarded. The flexibility gained during the months of the crisis will continue to advance, especially concerning forms of work and learning.’

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[16] Besides the positive effect to the health of the employee (see Section 2.3.1 Physiological Limitations), standing meetings take significantly less time compared to sitting meetings according to Bluedorn et al. (1999).

[17] The term *‘Co-working’* has been established to describe an open workplace structure shared by people with diverse job descriptions, diverse skill profiles who are not employed by a common company. Within co-working-spaces freelancers, employees from diverse companies, unaffiliated professionals, and even students are sharing collectively one workplace environment.

Based on the high importance of the propositions concerning effects on New Work and their relation to this research, an overview of the propositions is given in Table 7.

Table 7 - Ten propositions for the future of Industry 4.0 in the post-corona economy from Piller (2020).

1	Boost for digitalization and digital business models, but also a clear demand for scalable digital infrastructures and high-performance communication networks are becoming increasingly important
2	Flexibility and agility become the basis of competitiveness
3	Resilience of value networks as a new business case
4	Localization of manufacturing demands adaptation of product and process architectures
5	New ecosystems and marketplaces are emerging
6	Innovative revenue models are getting traction
7	Competence requirements are changing radically
8	*'Physical distancing'* of production: Remote services increased importance
9	Flexibilization of work fosters new forms of organizing and learning
10	Industry 4.0 as an enabler for sustainability

The transfer of knowledge already established within office designs is to be transferred to solve rising issues of the industrial workplace environments reasoned by the diverse and ever-changing conditions within dynamic markets. Consequently, a concept regarding the driver mentioned in the discussion above is outlined within Section 5.1.

The flexibility of production systems

As commonly agreed, megatrends such as globalisation and digitalisation lead to a high dynamic of markets. The resulting volatility is regarded as a challenge for the future production system and demands a radical change in the industrial landscape (KUKA AG 2016). To remain competitive within a fast-changing market system, flexibility and individuality of production and logistics are in demand. Moreover, Vogel-Heuser et al. (2017) used the term *'versatility'* to meet the requirements of unpredictable market changes and highlight the value of a production system which can be transformed according to the order situation with minimal effort. Furthermore, the increasing customization of products and small batch sizes requires the manufacturer to overcome the limitations of traditional production and maintenance systems.

The concept of a flexible manufacturing system enables a highly adaptable production (KUKA AG 2016; Dostal et al. 1982). The KUKA AG (2016) terms this system as *'Matrix Production'* and shows how this conceptual framework separates logistics from production in future factories (see Figure 22).

Figure 22 - The Matrix Production - (R-Robot). Adapted from: KUKA AG (2016).

The principal value results from the flexibility of the configurable production cells, where robots handle and add in parts. Tool magazines next to the robot supply the adaptation of the end effector to the work task. Parts and further tools are transferred from the warehouses and tool stores to the specific cell, i.e. using AGVs. Overall, the production is controlled by a decentralized intelligence: all parties are networked. The workpieces, the machines and the process itself constantly deliver and exchange process data (KUKA AG 2016). These flexible and scalable systems provide an attractive perspective on future production.

According to this, Hompel and Henke (2014) additionally argue that in a system that must adapt continuously to the conditions, there is no optimal location. Rather, the production must be able to move its location.

To create an industrial workplace environment that is adequate for human needs, science and industry deal with the application of knowledge for workplace design. There are numerous research activities recognisable that have an anthropometrical workplace design as their goal and address this question from different directions as follows.

Integration of Human-Robot Interaction

As reported earlier, the COVID-19-pandemic fundamentally affects the future of office work and work in the industry. Furthermore, the pandemic has shown that local production is particularly stable in contrast to global supply chains. Barthels (2020) states that robotics will be the driving force to ensure that high-wage countries keep up with the competition when companies start to produce locally again. Consequently, to enable successful integration, researchers and professionals are searching for applicable systems for hybrid robot-human teams. Much work on the potential of HRI has been carried out from the technical point of view, e.g. on how to make the robotic system interact safely. Approaches for the system design for HRI are given as follows.

The BionicWorkplace by Festo demonstrates in a conceptual way of how technological developments from the field of HMI and HRC can be integrated into workplace design (FESTO 2017, 2018). Another investigation from research institutes is given by the Fraunhofer Institute for Factory Operation and Automation IFF which also developed new technologies and components for safe interaction between operators and robots, including the mobile robot Valeri and the ColRobot (Fraunhofer IFF 2016a).

As reported in the discussion earlier, employees are influenced by the system they are surrounded by, including autonomously acting machinery, e.g. robotics. Besides the factors given above, emotional aspects also affect human performance within this workspace environment (Steinmetzger 2007).

Performance and Well-Being

Dul et al. (2012) detected an effect of HFE design, which describes the correlation of two related systems: By fitting the environment to the human, performance and well-being can be achieved (see Figure 23). They further highlight that performance, e.g. productivity, efficiency, effectiveness, quality, innovativeness, flexibility and well-being, e.g. health and safety, satisfaction, pleasure, learning, personal development, are influencing each other.

Figure 23 - The correlation between performance and Well-being related to HFE design. Adapted from: Dul et al. (2012).

Analogous, the operator's willingness to perform is closely related to motivation and drive. An increase of well-being supports the quality of performance, but correspondingly performance influences the well-being. Adapting the environment to human needs finally may increase both performance and well-being. Equally, workplace design can be used as a motivator (Chandrasekar 2011). The motivation that positively influences the well-being correspondingly increases performance.

The theoretical considerations on HF indicate that HMI is based on several processes and requirements that are correlated and cannot be considered separately. Therefore, all three dimensions of HF, physiological, cognitive, and organisational, are required to be considered simultaneously within development processes for workplace- or interaction systems. Moreover, the knowledge gained needs to be applied to adequate design solutions, especially validated strategies from office design show high potential to be transferred to industrial workplace design.

HMI within the digitised industry is characterised by high complexity. Technological progress has introduced new forms of robots, autonomously acting machinery and artificial systems that have fundamentally changed the way of HMI. Within this process, design and engineering must develop intuitively operable and assisting systems within suitable workplace environments to best support the most vulnerable factor of the factory – the human operator. Those systems need to satisfy much more than the safety standards or a pleasing aesthetic: to fulfil the working tasks required within a highly complex system, the relief of the operator in all three levels, physiological, cognitive, and organisational is paramount.

HF must be carefully woven into multisensory (visual, haptic, auditory) designs of workplaces, workplace environments and interaction systems, which respond and behave in line with the confirmation of expectations of the operator. This offers sustainable added value in psychological and physiological strain relief and leads to a build-up of experiences of satisfaction and consequently results in a high level of acceptance of the systems.

2.4 Issues identified within the Contemporary Industry

The rapid development of computer technology changes industrial production significantly. Researchers and industrial experts agree that after mechanization, electrification and computerization of industry, the entry of the Internet of Things (IoT)[18] and digital services into the factory heralds a 4th Industrial Revolution (Acatech 2013; Roth 2016; Westkämper et al. 2013). Many authors define the complete networking of production and logistics processes as a new term: Industrial Internet of Things[19] (IIoT) (Andelfinger and Hänisch 2017; Pflaum et al. 2014).

The term *'IIoT'* is equated with the term *'Industry 4.0'* (I4.0) which refers in particular to the digitised industrial environment in Germany (Buhr 2015). However, there is still a lack of a generally accepted, scientifically formulated definition describing the digitalisation of the industry. The term *'digitised industry'* will be used within this thesis to refer to the reunification of the I4.0 and the IIoT. In this context, CPS evolved as a significant element (Westkämper et al. 2013). These systems contain autonomously operating machines, storage systems and resources which continuously exchange information (Acatech 2013).

A growing body of literature examines the features and requirements of the fast-changing production processes within the digitised industry. In their analysis, Westkämper et al. (2013) highlight the new quality of linking production systems as one of the main advantages of the digitised industry. Individual customer requirements can be taken into account and even the industrialized manufacturing of individual pieces and production for small batch sizes is profitable (Acatech 2013). Approvingly, Hompel and Henke (2014) comment that a system needs to accommodate the circumstances at all times, e.g. the industrial plant of the future is moving its regional location effortlessly. Additionally, Acatech (2013) draws attention to current challenges such as resource and energy efficiency, urban production and demographic change which are tackled by the digitised industry.

A challenging area in the field of the digitised/high-risk process industry, explicit workplaces for HRC and HMI within the automated system results from human errors. Waard et al. (2015) reported on the documentation of several HF issues in the automatization design.

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[18] Xia et al. (2012) use the term Internet of Things (IoT) to refer to the networked interconnection of everyday objects. Internet of Things (IoT) the term refers to the network of physical objects (KUKA AG 2016.).

[19] Jeschke et al. 2017) differentiate the IIoT from the IoT as an information network of physical objects which refers in particular to industrial environments. In this context, literature also introduces the term Smart Factory (Acatech 2013; Andelfinger and Hänisch 2017; Buhr 2015; Roth 2016).

Today, industrial workplace-design for HMI has been developed from a technology-centric point of view (Bauer et al. 2017; Bouchard 2018; Kries et al. 2017). Consideration of user-centred demand is insufficient and the holistic/systematic method for designing workplaces for HMI and HRC concerning a holistic view on HF issues within digitised industry is uncertain. In contrast, the Federal Institute for Occupational Safety and Health in Germany suggest a holistic approach, which should place greater emphasis on the interaction between human and machine within working systems (Robelski 2016). The humanization of the workplace is expected. Furthermore, the German Federal Ministry of Education and Research (2018) postulates to involve users in the design process.

Reviewing recent literature shows expectations of the industry to the changing role of the operator. The digitised industry is characterized by dynamic processes with increasing complexity. As a result, the number of monitoring tasks and the need for a corresponding qualification level of employees increases (Andelfinger and Hänisch 2017). Experts argue that within the education of future employees, skill-fields need to be re-evaluated and adapted to the requirements of the interdisciplinarity of future tasks (FESTO 2015). Therefore, Andelfinger and Hänisch (2017) assume that problem-solving skills like creativity and flexibility play a crucial role. Approvingly, Acatech (2013) argues that an equally important feature of the digitised industry results from smart assistance systems which release operators from having to perform routine tasks and enabling them to focus on creative, value-adding activities.

In conclusion, the German Federal Ministry of Education and Research (2016) refers to the importance of assistance systems within a changing working environment.

To adequately develop those assistance systems for collaboration of operators and joint-arm-robots, the bundle of diverse competencies is paramount. Within an empathic and respectful manner, diverse teams uniting engineers, designers, professionals from various disciplines and representatives of the target group will be able to collectively tackle challenges. Consequently, professional designer and engineers of the future should be educated to face those issues. The following section describes the shifting role of industrial design and addresses necessary changes in education to be able to design interaction systems regarding HF issues.

2.5 Shifting the Role of Industrial Design

This section aims to lay out a brief review of design history, as well as seeking to discuss the contemporary role of industrial design related to changing requirements.

2.5.1 The History of Industrial Design

The character of the industry is changing revolutionary. In parallel, product design is simultaneously adapting. During the first phase of design history, design was craft-rooted and as soon as the industrial revolution started, design was utilized to create applications to science, engineering and manufacturing (Design Council 2007).

Within the last decade the interaction and experience have become paramount. Nowadays design is moving to organisational structure, e.g. marketing, corporate identity, workplace systems and company culture et cetera (Sanders and Stappers 2008). In this context, design is utilized as a tool to adapt to technological progress but is increasingly oriented on human needs. Accordingly, design shapes the nature of environments in which humans are moving and operating. Finally, design creates the basis to enable communication and interaction. Likewise, Sanders and Stappers (2008) concluded that the industry has been primarily manufacturing-driven, afterwards technology-driven and recently, motivated by the stagnation of the technology push, the user experience is in the focus of investigations.

In contrast to the technology-driven industrial design area, human-centred approaches react towards rising complexity and versatile conceptions of the usage of products (Krippendorf and Butter 2009). Within the technology-driven area, products have been predefined and developed for a certain usage not concerning individualisation. In recent years, designers have been developing products that take into consideration that products are used and experienced by people in different ways. As Krippendorf and Butter (2009) put it:

‘Human-centeredness acknowledges the role of humans in actively constructing artifacts–conceptually, linguistically, and materially–being concerned with them, handling them, and putting them to work.’

Krippendorf formed the term *semantic turn* to introduce a paradigm shift (Krippendorf and Butter 2009). Thereby human-centred approaches enable agile utilization instead of rigid industrial design. The user added-value through experiencing the design is also highlighted by Norman. As he puts it:

‘Even if technologies may change, the fundamental principles of interaction are permanent.’ (Norman 2013).

Krippendorf and Butter (2009) further suggest four conceptual pillars that support human-centeredness:

- Second-order understanding, as understanding other’s understanding

- Meanings[20] for artifacts in:
    - use
    - genesis or life cycle of artifacts
    - language
    - ecologies of artifacts
- Networks of stakeholders
- Interfaces

Nowadays, within a period which is characterised by high dynamics of ever-changing conditions, the role of industrial design is again undergoing radical changes. Cooper et al. (2009) assume design thinking will replace designing artifacts, so that graphic, product, and service design will become an output of processual debate.

2.5.2 The contemporary Role of Industrial Design

In the enquiry into the role of design within the I4.0, IXDS Human Industries Venture (2018) reports that design improves manufacturing processes when involving all stakeholders from the early stages. Accordingly, the user-centred design landscape is developing into an environment of co-creation (see 2.3.3 Organisational Applications, Co-creation), where users are involved in the design process from the early stages (Sanders and Stappers 2008).

Acatech (2013) emphasizes the importance of workplace organisation and design: self-responsibility of operators should be supported by participatory workplace design and to support lifelong learning. The literature exemplified how shop-floor operators have been treated as machine-like assets instead of recognising the value of the creative potential of the operator as they often create workarounds to improve processes (IXDS Human Industries Venture 2018). Similarly, Norman (2013) outlines that *anyone* can design, due to their creative potential. Creativity is not a unique selling point for a designer. Corresponding, Steelcase Inc. (2017a) affirms the necessity to support creativity at work to create value for business and society. Furthermore, Steelcase Inc. (2017a) provides the following assumption to outline the significance of creative problem solving:

[20] For Krippendorf, meaning is deeply related to how people interact with technologies. As Krippendorf and Butter 2009) put it: 'The meanings of an artifact are manifest in the set of contexts into which a community of its stakeholders places them – deliberately, i.e. to a degree better than chance.' Consequently, Designs must be developed considering the broader context into which the design will be integrated.

'As problems become increasingly complex, creativity can no longer be viewed as purely an artistic pursuit, but rather a way of thinking and a set of new behaviours that can be applied to a wide range of issues, leading to new ways of working.'

Indeed, product design is not only the aesthetic design of the exterior form but also rather the appropriate design of tools for interacting with the environment and the design of processes themselves. Similarly, product design can be utilized as a powerful tool for meeting the requirements of volatile markets, the requirements of the changing processes of the environment and society e.g. demographic change, lack of skilled operators, decentralization of production systems and globalization. Within the increasing automation of the industry, Lee et al. (2017) argue that the need for careful consideration of HF in design becomes more important. A contemporary design considers all ergonomic aspects and at the same time considers the psychological significance of the design to the employee.

An understandable interaction while using a product is perceived as a positive experience and provides a motivating added value to the user (Design Center Baden-Württemberg 2017) – see 2.3.3 Organisational Applications. This psychological process happens subconsciously while good design unfolds its effect inconspicuously (Rams 2014). In summary, IXDS Human Industries Venture (2018) states that design will enable the development of systems which empower skilled operators and non-experts simultaneously and make processes usable for a huge number of people. Further, experts illustrate the change from the single-working, individual designer to the teamwork of designers and interdisciplinary professionals within the development-process and highlight that further, the integration of co-design acts as a major driver of the creation method (Cooper 2017). Supporting this potential for creativity and additionally enable new high-flexibility forms of diverse cooperation teams will become the task of the future workplace design.

To describe the future of design, Norman (2013) refers to his investigation that design is becoming a research-based discipline which combines applied and theoretical approaches. Similarly, Cooper (2005) agrees to this by highlighting that the profession of design research is a valuable discipline to society to gain knowledge about the understanding of the relationship between the material world and human interaction. Investigations into the profile of professionals within this field were carried out by Sanders and Stappers (2008), who argue that the boundaries of classical role models are disappearing so that researchers and designers may be the same person.

Changing character of design education for future generations of design/engineering students

IXDS Human Industries Venture (2018) concludes future designers will play a crucial role as experts and collaboration partners connecting stakeholders. Moreover, the designer will conduct the creative development process and becomes the connector for interdisciplinary and highly diverse teams. To illustrate, the CEO at the company IDEO, Tim Brown (2005) uses the term T-shaped people to refer to employees who have a principal depth skill, comparable to the vertical stroke of the letter T, and also are empathic so they can connect with other members of the team across disciplines. Figure 24 illustrates the transfer and combination of knowledge by Inter-Disciplinary Experts, that is fostered by communication skills (Thoring and Müller 2011).

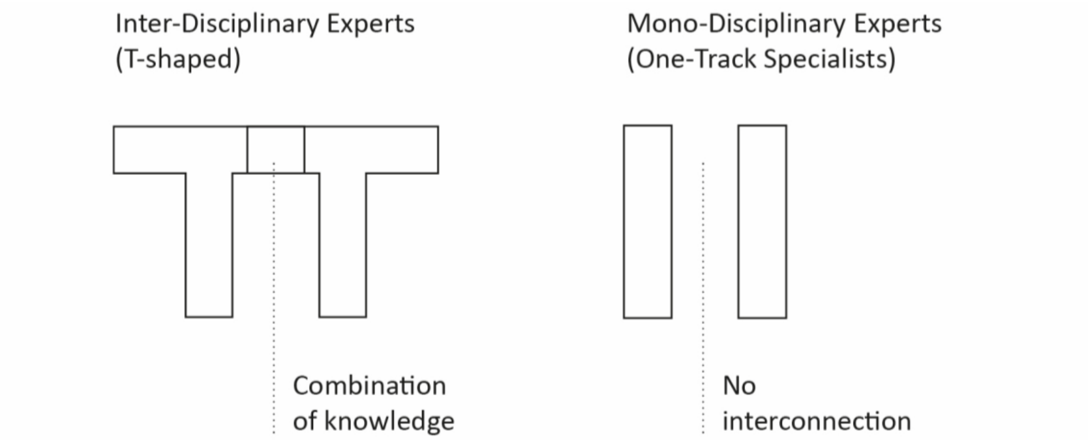


Figure 24 - Visualisation of Inter-Disciplinary Experts in contrast to Mono-Disciplinary Experts. Adapted from: Thoring and Müller (2011). No Creative Commons Licence.

The empathic ability of T-shaped people is illustrated by the horizontal stroke of the letter. As Brown (2005) put it:

‘They have a principal skill that describes the vertical leg of the T – they’re mechanical engineers or industrial designers. But they are so empathetic that they can branch out into other skills, such as anthropology, and do them as well. They can explore insights from many different perspectives and recognize patterns of behaviour that point to a universal human need. That’s what you’re after at this point – patterns that yield ideas.’

Similarly, Øyan (11/9/2018), Professor of Industrial Design at the Oslo Metropolitan University, postulates a strong need for communication and interaction skills for students, but in parallel affirms the need for continuous competence development from the lifelong learning perspective. He further reflects, that the increasing number of non-linear design students, is challenging Higher Education. Within volatile markets, the employment landscape is becoming increasingly dynamic. This leads to constantly changing demands of competence development and re-qualification. Consequently, Øyan highlights the value of facilitating competence exchange and collective learning within the practice- and work-based Higher Education by utilizing problem-based learning. This is further important to support exchange and cooperation within highly diverse teams with several knowledge backgrounds. For the future of design education, this means offering a learning environment that provides individualized study progress and values the diverse entering competencies for creative solution development.

Besides the acquisition of knowledge, problem-based learning gains several advantages as it fosters active development of generic skills and attitudes as follows (Wood 2003):

- Teamwork
- Chairing a group
- Listening
- Recording
- Cooperation
- Respect for colleagues' views
- Critical evaluation of literature
- Self-directed learning and use of resources
- Presentation skills

Through the problem-based learning framework, the development of lifelong learning skills is stimulated on both sides – this form of the educational framework requires a steady adaptation on the part of the students but also of the tutors (Birkenbihl and Birkenbihl 2018). Wood (2003) claims that problem-based learning requires the tutor to take the role of a facilitator rather than acting as the provider of information. As a prerequisite for successful implementation, Wood (2003) further draws attention to the development of tutors who are subject-specialists, understand the curriculum and in parallel show excellent facilitation skills.

The demand of scientific, problem-based framework within Higher Education to enable T- Shaped education is in line with the views of Rachel Cooper, Chair of Design at the Lancaster Institute for the Contemporary Arts. Cooper et al. (2009) postulate an imminent future for the professional field of design, where designers are focussing on strategic design. Additionally, they assume that design incorporates into interdisciplinary fields, e.g. Design Psychology, Science of Design, Ecology Design. Similarly, Reventlow and Thesen (2019) describe the designer's new role as a cultural change agent who expands design from product to strategy and facilitates humanisation of changing environments within the digital transformation.

As this research reports in Section 4.2 Survey and Interviews, a series of in-depth interviews with professionals from Design, Engineering, and merged-profiled professionals within the field of the digitised industry has been undertaken. At this point, a summary of three opinions on the requirements for successful design and development teams are given. The written recordings of the full interviews are given in Appendix B.

The company, Festo AG & Co. KG is a global leader in pneumatic and electrical automation technology. Dr Elias Knubben, Head of Research and Innovation, Senior Vice President at Festo illustrates how product design satisfies the industry now and in the future by the reflection of the agile design team approach at Festo. Festo's development team is interdisciplinary in nature. At the department, experts with knowledge backgrounds as computer scientists, designers, biologists and control engineers are sharing a common workplace, developing collaboratively. Knubben highlights that this constellation is not only perceived as motivation and fun but also enables the members of the team to gain knowledge from previously unfamiliar research fields. The application of highly agile methods such as interdisciplinary teamwork and co-creation requires strong communication skills to be able to transfer the expertise. This is the basis for an understanding of the context for product development. As Knubben puts it:

'Therefore, we have generalists in our team, who mind the big picture, and specialists, who dive deep into technical problems. The team has a playground and the freedom to create better solutions together.'

Inline, the interviewee Dipl.-Psych. David Kremer, competence manager at Fraunhofer IAO highlights how highly diverse teams ranging from psychologists, curative education nurses, computer scientists, engineers and business economists are successfully working together within a participatory process on the development of projects at the Fraunhofer IAO, e.g. on the AQUIAS project, that illustrates how robotics can support people with and without restrictions in the joint completion of tasks (Kremer et al. 2018). Working in diverse teams is becoming more and more important for the successful development of solutions to meet the challenges of the future. As Kremer puts it:

'Moreover, the interdisciplinary work will increase in importance for engineers and designers. Communication between the members of the team is the basis for successful project development.'

Likewise, the industrial designer Andreas Hackbarth gives an insight into his opinion on the future of industrial design. After completing education, Hackbarth gained experience in the design profession for more than three decades, e.g. working for the Siemens Design Department at BSH Hausgeräte GmbH, one of the largest home appliance manufacturers in Europe. Hackbarth has been one of the first design-students of the German industrial design icon Dieter Rams, who has strongly influenced Hackbarth's formative years and therefore his view on design solutions and the role of designers within the creation process in general.

Hackbarth warns of over defining product development processes and highlights the need to involve the designer as connector within the entire development process. Especially against the background of disruptive processes, e.g. world-wide conflicts and pandemics the need arises for agile adaptation. As design has moved from modern arts and crafts attitude towards industrial design in retro perspective, Hackbarth highlights the need for training future design students towards multifaceted personalities, being able to connect over disciplines and country borders to collectively adapt to the changing demands of future challenges. Considering the future of design education, he postulates the need for more international cooperation, more international academic exchange, e.g. obligatory semester abroad, more offerings for international studies, and dual studies in design linked to industrial companies. Similar to Knubben, Hackbarth draws attention to the education of the future of design professionals as contemporary input of a designer must be to represent the *all-rounder* in collaboration with specialists. Furthermore, he draws attention to a strong attitude as one fundamental competence. As Hackbarth puts it:

‘It is a major challenge for a designer to live attitude and aspiration in his professional life. Not just during the cooperation with the specialists but unfortunately also in daily work with colleagues in design. I never met a designer who claimed *not* to have an attitude. But facing adversity it is a troublesome road to stay true to yourself, to exemplify your position and to push your ideas.’

The designer of the future needs to consider technical competences, but further needs to be able to constantly adapt to emerging technologies and they must be prepared to solve unpredictable problems using collaborations to gain and apply knowledge from a broad scientific community. Of particular importance in the training of designers and engineers for dealing with the requirements of the future will be the training of self-empowerment to approach a research question. Thereby, the key competence is the ability to be able to analyse the structure of a design problem on one’s own initiative, individually as well as in co-creation processes, and further, be able to independently search for adjacent professionals and get connected with them to create an equal working team. Tutors need to be facilitators within these learning-processes who foster as a supporter of the personal development of every student individually.

This literature review and the results from the interviews made clear how recent developments lead to an increasing need for an alternative future of the design sector. Furthermore, this section illustrated how the transition to interdisciplinary, problem-based education in higher design education for design- and engineer students is postulated by professionals.

As problems become increasingly complex, students must be prepared to be able to connect diverse teams, containing skilled professionals from several disciplines but also integrating co-creation with users who bring into the process their creativity and contribute to design with unexpected ideas. This requires a strong character profile, as it means being able to put your own needs behind those of the target group. Lone fighters who fight for their ideal and personal advantage will find it difficult to act in multifaced teams for a common good, but Design education has not kept up with the new demands of the 21st century as pointed out by Meyer and Norman (2019). Besides, a deep content-based knowledge base, the ability for coordinating communication is essential for future designers to mediate.

As one sign of this, Meyer and Norman (2019) identified the lack of designers in high-level positions within organisations and government. Changing the character of design education is paramount to overcome future challenges. Meyer and Norman (2019) suggest a broadening of the material taught at design schools to tackle designers' expanded challenges ranging from problem-finding and solving to encompass societal issues. Furthermore, they formulated the following areas that should be addressed within design education:

- Performance challenges
- Systemic challenges
- Contextual challenges
- Global challenges: dealing with complex sociotechnical systems

2.6 Summary of Chapter 2

- This chapter introduced the scientific field of interaction design and HFE and showed its high potential for the development of applications that adequately assist operator's interaction with join-arm-robots within high dynamic environments such as the digitised industry, assisting an intuitive system for HRC/ HMI concerning all levels of HF.
- Moreover, this chapter detailed issues identified within the contemporary industry from the literature review and gave a general panorama of research on assistant scenarios that shows different approaches which aim to support the operator within the industrial environment.
- Finally, this chapter derived issues for changing the character of education for future generations of design/engineering students to overcome the issues with high complexity such as the issues identified above.

This chapter draws attention to the need for a comprehensive, systematic solution for industrial workplaces particularly that considers operator needs while working collaboratively with joint-arm-robots. A holistic solution is widely not known and a specific application regarding cognitive strain relieve at production workplaces is missing. As a result, this work seeks to deliver a framework for the design of industrial workplaces to relieve workers when interacting with joint-arm-robots.

Chapter 3. Research Methodology

A mixture of qualitative and quantitative methods has been employed during the study, aiming to explore the knowledge of HF and its applications within the digitised industry, in particular in clarifying how people are influenced whilst working with autonomously operating machines such as robots. These methods helped the author to explore/understand the in-depth knowledge from different perspectives in terms of how the operator's strain can be reduced during interaction. The strength of qualitative research applications relates to research fields where the identification of crucial elements is impossible (Atieno 2009).

This PhD study focuses on investigating the interaction between humans and machine/system within a variety of/complex situations, hence the qualitative method helps the author in understanding humans' behaviour and attitude of the operators. To avoid the bias caused by the subjective interpretation of the results, quantitative research has also been used within the research. But quantitative methods in turn cannot respond flexibly to the unique characteristics of the operators and specific cases (Wetzel 2016; Winter 2000). Furthermore, Winter (2000) highlights the identification of statistical interchanges as one major strength of quantitative research, which is most relevant to answer research questions of this research within the second phase (see below).

Given these, the combination of advantages of both methodologies has assured the quality of this research. Creswell and Tashakkori (2007) believe that the mixed methodological perspective, using quantitative and qualitative approaches for research design, allows focusing on the entire process and parallels might emerge during the ongoing research work to enable answering research questions. Finally, the methodology has been structured into two phases:

Phase 1) qualitative/ inductive, empirical

The inductive method has been undertaken from specific investigation to general analysis, and practical study to abstracted theory. This method helps in generating the criteria for future workplace designs.

Phase 2) quantitative/ deductive

Quantitative method verified the theory generated from phase (1) by the evaluation method that analysing an individual's brainwave frequency and validating a conceptual prototype created based on the design criteria. The two-phased-structure method fits the *'Framework for Innovation'* embracing the methodology of the Double Diamond Process in Section 3.1.

3.1 The Framework for Innovation

The *'Framework for Innovation'* facilitates designers to face complex social, economic and environmental challenges (Design Council 2019).

The Framework for Innovation is a Human-Centred Design (HCD)[21] methodological model that was introduced/evolved over the decades by the British Design Council (Design Council 2007, 2015, 2019). The Framework for Innovation is characterised as a human-centred and participatory approach in product/system design. The Framework for Innovation is illustrated in Figure 25 and gives a comprehensive and visual description of the design process (Design Council 2019).

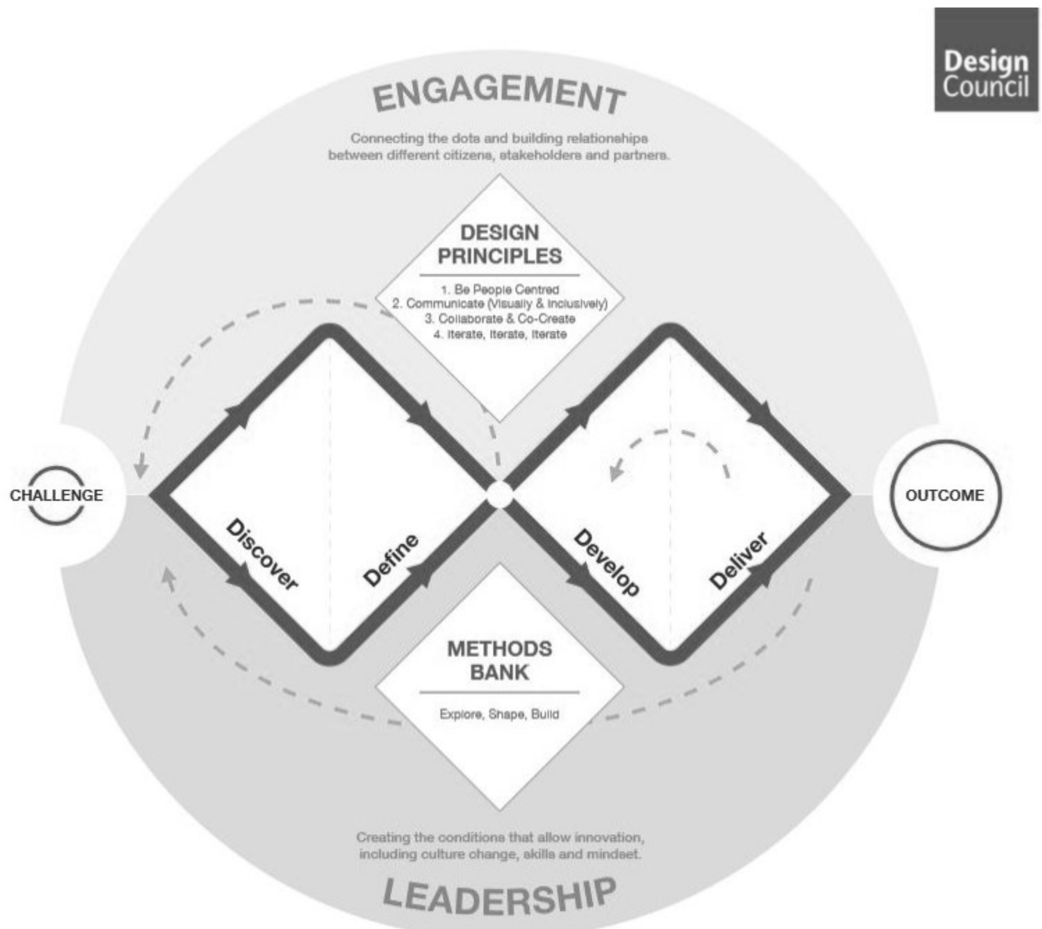


Figure 25 – Framework for Innovation: Design Council (2019). Design Council Double Diamond, created in 2004. No Creative Commons Licence.

[21] The HCD framework is included in DIN EN ISO 9241-210.

According to the Design Council (2019), the design principles are supporting the Framework for Innovations. Besides a mind-set, which is people-centred, communication skills, as well as the ability to collaborate and co-create, are highlighted by the Design Council (2019) as major design principles. Furthermore, the framework is supported by the engagement of the researcher to enable connection with all people involved and related to the process. Additionally, the process must be surrounded by adequate leadership, which creates the conditions, that builds up a trustful culture to enable innovations. The core of the Framework for Innovation is the Double Diamond Design Process.

The Double Diamond Design Process within the Framework for Innovation

The design methodology included in the Framework for Innovation is called the Double Diamond. The process commences from the *'Challenge'* at the first diamond:- a divergent phase initiates, where the research focuses on issues identification and provides a background for the research, then it opens up broad aims to seek a greater understanding of questions/problems, such as the 'Good design starts with a good understanding of people and the needs that the sought design solution is intended to meet.' (Norman 2013). After that, the study concentrates on defining the specific research area, the tasks include:

Discover.	The first diamond helps people understand, rather than simply assume, what the problem is. It involves speaking to and spending time with people who are affected by the issues.
Define.	The insight gathered from the discovery phase can help you to define the challenge in a different way.

Source: Design Council 2019

The second diamond starts with exploring possible solutions and generating a broad range of potential ideas, then the ideal concept will be selected for prototyping and testing, consequently, the refined product will be launched to the market. The diamond covers the following tasks:

Develop.	The second diamond encourages people to give different answers to the clearly defined problem, seeking inspiration from elsewhere and co-designing with a range of different people.
Deliver.	Delivery involves testing out different solutions at small-scale, rejecting those that will not work and improving the ones that will.

Source: Design Council 2019

The outcome stands as a result at the end of the process, e.g. a solution that works to overcome a challenge. In his analysis of the Double Diamond Design Process, Nessler (2018) used the phrase ‘Doing the right things’ to describe the purpose of the first diamond; ‘Doing things right’ for the description of the second diamond’s aim. Within a constantly changing environment, new challenges or technological progress can influence the process. Therefore, the knowledge gained, sometimes will lead the researcher to start again from the beginning, but with regards to the learned findings. This is visualised by the dotted arrows within Figure 25. Accordingly, iteration is also part of the design principles utilized within the Double Diamond Process.

The Double Diamond Design Process includes a method bank related to the HCD mindset. HCD is a design philosophy woven into the Double Diamond Design Process that describes the iterative cycle of design research. Norman (2013) divides the iterative HCD process into four different activities: Observation, Idea generation, Prototyping, and Testing which can be also found within the two diamonds. HCD represents a general approach in the design of interactive systems, such as UIs of software, smartphones, computer terminals and machines.

The approach of HCD provides significant benefits: An adequate workplace design eliminates stressors, increases productivity, builds up satisfaction experiences and supports mental and physical health. In addition, HCD aims to achieve a good user experience to increase the acceptance of the product. Good design aims to make a product easy to use and understandable (Rams 2014). To achieve this, the operators should be involved in the participatory HCD process at all phases of product development (Apt et al. 2016). This is in line with the design principles of the Framework for Innovation as described above.

The Framework for Innovation compared to other methodological frameworks

A compendium of models related to design and development processes, from architecture, industrial design, mechanical engineering, quality management, and software development gives Dubberly (2004). A list of thirty selected publications that incorporate reviews of design and development process models give Wynn and Clarkson (2018). Further Wynn and Clarkson (2018) developed an organising framework for design and development process models.

To be able to assess why the present research is utilizing an adapted approach of the Framework for Innovation a comparison with a selection of other methodologies from the field of complex linear models and cyclic models is given within the following.

A model of structuring problems and systems gives the VDI Verein Deutscher Ingenieure (2019) in the guide VDI 2221. The model for the design of technical systems and products starts from an ‘overall problem’ and ends with an ‘overall solution’. The Framework for Innovation instead replaces the term ‘problem’ with the term ‘challenge’ to broaden the focus of investigations. Further, the Framework for Innovation replaces the term ‘solution’ by the term ‘outcome’. Consequently, the Framework for Innovation allows conceptual conclusions as possible outcomes, e.g. criteria. The model of the VDI is characterised as a linear model, similar to the Framework for Innovations. While the VDI is focussed on the linear process of problem solving/classification of several types and connections between problems, the Framework for Innovation is open for finding problems along the running process. Moreover, the VDI 221 is task-related and approaches to gain specifications. The Framework for Innovation instead is focussing on the finding/definition of a problem/solution within a two phased process. Both approaches are utilizing iterative cycles to adjust the direction of investigation/development for optimization.

The model THEOC – theory, hypothesis, experiment, observation and conclusion – describes a framework characterized by a fixed procedure. Thought, iterative cycles are intended, the order of tasks is static. The classic goal-action feedback loop starts with a theory, then the generating of a hypothesis follows. Afterwards, the experiment is conducted/observations are made and transferred into a conclusion. This model is not considering the focus of the attention of the designer. Convergent and divergent phases are not included. Compared to the Framework for Innovation this model lacks of is agility since there is no opportunity to start the process with observations in order to investigate the field of the problem. Identifying unknown problem areas at the beginning of the process is neither considered in the VDI model as in the THEOC model.

Instead, the Double Diamond Design Process of the Framework for Innovation suits to investigate this present research´s questions by enables the researcher to start with an open focus into each of the two phases of the process. The focus on the track of a designer’s attention through the utilization of phases of iterative divergence/convergence is one main advantage of the model.

The divergent phases enable to identify and observe problem fields/driver and user-centred needs within a fast-changing, dynamic environment. The Double Diamond Design Process is not a goal-action-feedback loop. Following the divergence/convergence phases, the research is able to identify problems/solution along the way and adjust the investigations accordingly. This is a striking benefit of the methodological Framework for Innovation and therefore it is chosen for this research.

To be able to specify main hindrances toward the integration of joint-arm-robots for collaboration with operators the open focus at the beginning of the first diamond-phases supports the investigation. Based on the hindrances, criteria for workplace design to overcome those identified issues are specified within the second phase of the first diamond.

To investigate how cognitive strain while interaction with joint-arm-robots can be detected and investigated, the first phase of the second diamond of the Framework for Innovation can be utilized. To seek approaches that can reduce operators' strain during their interactions with joint-arm-robots the last phase of the second diamond of the Framework for Innovation can be applied.

With its conceptual character, the Double Diamond Design Process suits to be applicable to a broad field of investigations but lacks on delivering explicit activities and targets related to specific application fields. Therefore, there is a need for an adaption of the Double Diamond Design Process towards the specified application of the field of HF and its needs within workplaces for collaboration with joint-arm-robots. The adapted journey Model that is related to this thesis' hypothesis and the specific application field is described in 3.2.2 Development of a conceptual Framework of the Research. Explicit targets and activities have been added to support the framework. Alongside with the selection of appropriate methods and the best practice example, this proves the novelty of the methodology utilized within this present thesis.

The following section gives a description and discussion of utilized methods related to the methodology and used to answer the research question of this thesis.

3.2 Adopted Approach - Conceptual Framework as a specified development of the Framework for Innovation

Given discussions in Chapter 2, the role of industrial design has been shifted from the technology-driven stage to the user-centred design-driven. Technology revolution results in the interface of products/systems/workplaces that are more complex, in particular those of multimodality interfaces such as aircraft cockpits, ship bridgeboards and workplaces that displayed a large amount/variety of information which challenges users to recognise/interact with. Nowadays, human error causes the most accidents in many fields (Whittingham 2004), in the majority of instances, it is the result of the inappropriate design of equipment/system or procedures (Norman 1982). Norman (1982) further explains how the poor design of the controls/interfaces is most often the culprit and in many cases, an HCD effort could eliminate most errors.

HF is a scientific discipline that is concerned with the understanding of the interactions among humans and other elements of a system. The knowledge, in particular, product semantics is a language that helps people to understand and interact with products easily and efficiently. Designers rely on this language to communicate with users; to express functions, reliabilities and characters through forms, material/textures and semiotics.

This chapter discusses the design of a conceptual framework of this research, that based on the development hypothesis re HF and its influences, aiming to find a tool, which provides reference points back to the literature to assist the author in making sense of the data, and to develop a structured approach to communicating the findings. This is a significant step in this research, and core to this thesis.

3.2.1 Hypotheses Development

Chapter 1 and 2 have outlined that the complex processes in the digitised industry influencing system-designs for HMI. Therefore, to overcome critical issues identified within the study, the hypotheses were developed based on the knowledge learnt from the literature review.

(1) All three levels of the HF impact the workplace design within the digitised industry.

The ideal workplace/environment must satisfy physiological/ psychological and organisational requirements. Ergonomically correct design is a prerequisite for adequate workplace design. The cognitive environments need to be decluttered of irrelevant cognitive signals, to support rapid cognitive information processing and providing the operator with positive effects on the performance and wellbeing. The organisational structure must support flexible working hours, as the establishment of an agile organisational architecture forms the root of flexible/persistent working culture. Meanwhile, knowledge of office design will benefit the concept of industrial workplace design.

(2) Validated design criteria steer designers'/engineers' future design practice.

(3) Assistance systems relieve operator's strain and therefore lead to high acceptance towards HMI and HRC.

Collaborating with autonomously operating machines such as robots causes operators to feel strained due to the artificial character of the movement of machines. The findings demonstrated that indicators will help operators to forecast the movements. An assistance system that applies the HF as discussed in hypothesis (1) will improve/integrate the HMI/ HRC.

(4) A method of monitoring/recognising mental load enables design practitioners/researchers to manage the cognitive load proactively.

In order to establish an HCD framework to assist design practitioners/researchers in workplace design, this research clarified some key factors that will improve user experience/interaction in releasing operator's strain and increasing acceptance of the CPS. Section 3.2.2 introduces a conceptual framework that was developed based on the hypothesis.

3.2.2 Development of a conceptual Framework of the Research

A conceptual framework is a physical, mathematic or logical representation of a system of entities, phenomena, or processes, and is a simplified abstract view of a complex reality (Guo 2012). A framework model may be presented in different ways; however, visualising the route of research appears to be a conventional approach to demonstrate key factors within a framework. Figure 26 introduces a journey model of the framework that was developed based on the hypotheses. The model introduces the HF impact, assistance system effort, criteria benefits and methodology support.

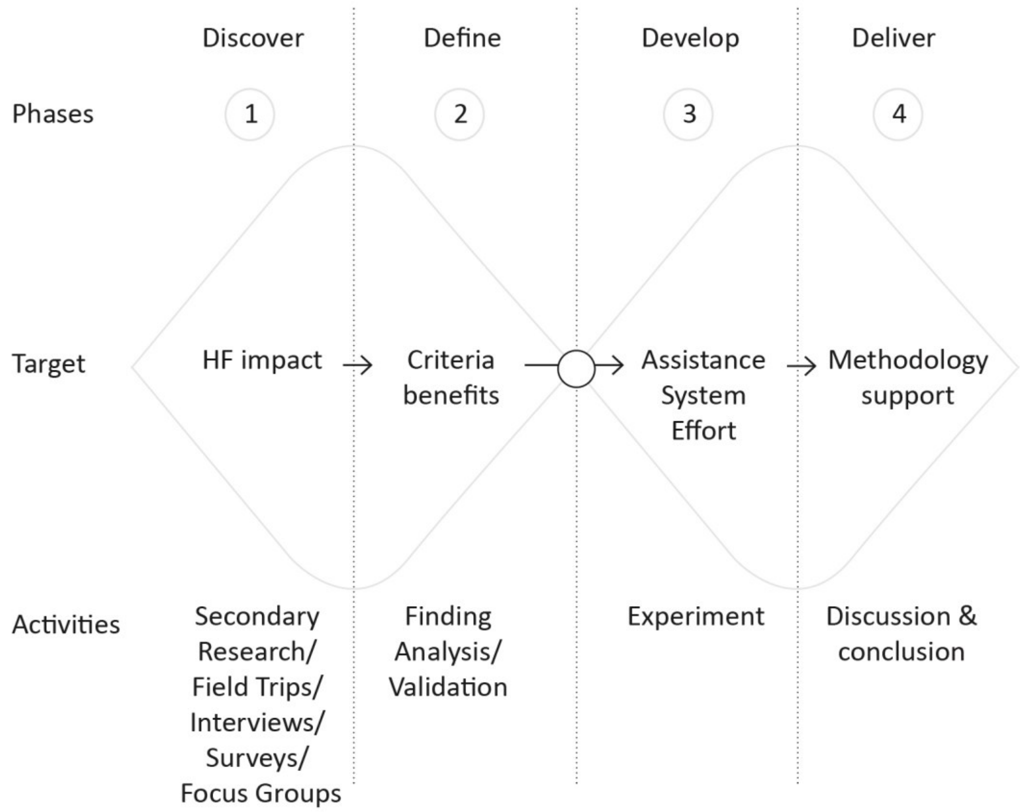


Figure 26- Conceptual framework of the present thesis.

The journey starts from phase one: the secondary research (literature reviews), field trips, interviews, surveys and focus groups to clarify issues of existing workplaces within digitised industry, together with reviewing the HF impact that leads to defining the design criteria at phase two. An experiment was designed/conducted at phase three, which includes a prototype of workplace design (an ideal concept/solution) that was generated based on the design criteria to evaluate if the assistance systems can help the operator perform well in HMI and HRC.

Finally, a method has been developed at phase four, aiming to support design practitioners /researchers to manage the cognitive load proactively. This is an evaluation approach to detect objectively the operator's workload while working with the demonstrator (see Chapter 5 - A controlled experimental Project). The framework has been related to the Double Diamond Design Process as a methodological principle.

In detail, appropriate methods are presented and discussed in the following section.

3.2.3 Development of the ideal Research Methods for this Study

Woven into the Double Diamond Process, the methods bundle of this thesis follows the Design Thinking IDEO Card process (IDEO 2003), that consists of *learn*, *look*, *ask* and *try* phases (Figure 27). The process commences from a broader frame of references such as issues identification, user's aspirations and expectations of the industry to narrow solutions that include experimental prototype, testing and evaluation. Step by step, the study starts from practical to theoretical and from the general to specific.

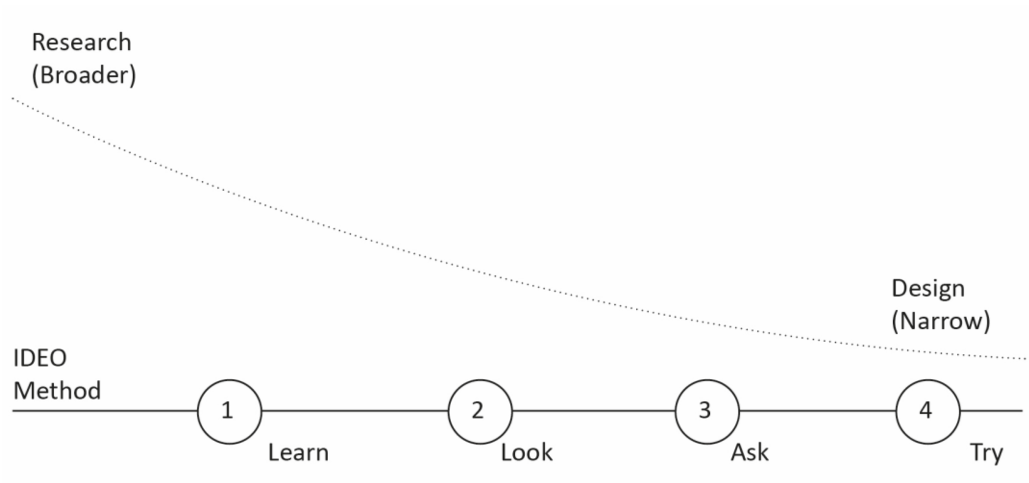


Figure 27 - Stages of IDEO method.

Given that the British Design Council has limited the method portfolio into 25 design methods, and accommodating research questions identified within this study (see Figure 28), appropriate methods for this research have also been selected from the method bank given by Martin and Hanington (2013) to further extend this portfolio. This comprehensive research method-bundle selected to answer the research questions, builds an intersection with methods given by the Design Council (2019).

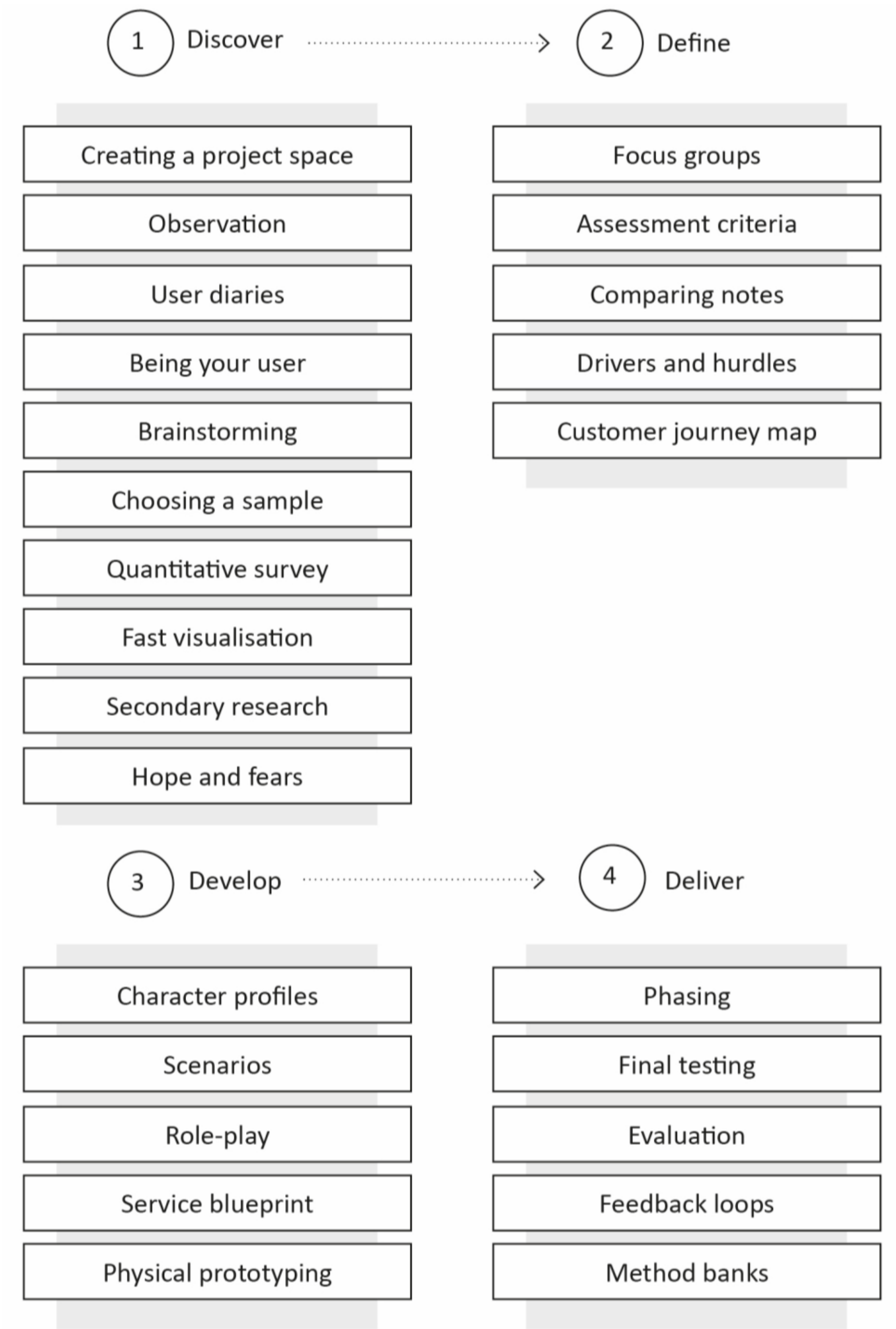


Figure 28 - Methods related to the Double Diamond Design Process. Adopted from: Design Council (2019).

The resulting methods-bundle selection follows the double diamond phases that apply HCD into the four phases: Discover, Define, Develop and Deliver. The methods bank consists of unstructured approaches in interviews and structured prototyping and evaluation methods, it also fits the IDEO process. Given the discussions above, general knowledge has been established in secondary research (see Chapter 1 and 2). The following research methods were employed within the study, aiming to fulfil the aims and objectives of the research.

The following sections present the methods selected for the fieldwork and give an overview of each strength and limitation identified.

3.2.3.1 Explorative research - Empirical Field Trips to the Industry

In order to identify working processes/conditions and the environment of digitised industry, and to clarify working tasks which are characterised by HMI, a number of empirical field trips were conducted in a variety of companies/organisations. These include field trips to the Odense Robotics Cluster in Denmark, consisting of Danish research institutes and industrial manufacturers such as the Odense Robotics Start-Up Hub, Mobile Industrial Robots A/P, Universal Robots A/S and Gibotech A/S. together with field trips undertaken in Germany-based research institutes such as Fraunhofer, and industrial manufacturers such as Franka Emika GmbH, Mebak Metallbau GmbH and Aero-Coating GmbH.

Exploratory fieldwork has been undertaken at different organisational levels, from high management to operational teams, that enables the author to see the whole picture of various requirements in the research field. Fieldworks were conducted at national and international manufacturers that helped the author to comprehend a variety of circumstances that are provided with hybrid Human-Robot Teams. On-site visits provided opportunities to observe the real-world environment and have chats with employees face to face while they were in their working conditions. This also helped the ergonomic analysis by collecting information about the status quo on various industrial sites.

Strength and weakness of explorative research

Explorative research appears to be a reliable method to gain a realistic insight into phenomena, artefacts, event-related behaviour, interactions and the environment (Martin and Hanington 2013). It provided a close/realistic view on the role of the operator due to the empathic perception of workday procedures, tasks, and challenges. In addition, this method enables the author to have an opportunity to chat with the employees on site. However, on-site visits may change the behaviour of the employees when feeling observed, especially when the researcher enters the site accompanied by a supervisor.

Furthermore, empirical field trips can be criticised due to being time-consuming, both for the researcher and also for the participants, particularly the gatekeeper who is accompanying the researcher while conducting the study. This is mainly given in safety-critical areas as it is suited to the industrial environment. Furthermore, the methods might lead to interruptions within the work procedure. Additionally, this method suffers from only having a short period spent with the subjects, so important observations can stay unidentified due to the narrow time window the researcher spends on site. Furthermore, observations might be influenced by the expectation of the researcher (Rosenthal and Fode 1963).

Besides the fact that serious criticism of empirical field trips is potentially influenced by researcher's subjectivity, this ethnographical method is considered as a powerful tool to emphatically dive into the context and issues of the real-world scenario. The basic requirement is the establishment of a trusting interpersonal relationship so that the scientist can experience behaviour that is as unaffected as possible.

3.2.3.2 Interviews with a target Group of Users from Industries

Structured/semi-structured interviews have been conducted at the *'Learn'* and the *'Look'* phases of this research. Interviewees range from operators, representatives from high management level, representatives from politics, design/engineering professionals, researchers from the field of robotics, automation, production engineering, ergonomics and workplace design and authorities from industrial design. As a part of traditional/qualitative research methods, interviews enable the direct collection of experience, perception and opinions (Martin and Hanington 2013; Kuniavsky 2003). Compared with questionnaires, interviews offer a better opportunity for a face to face contact with the interviewees, to discuss questions with more details accordingly.

Strength and weakness of structured interviews

An interview is one of the most feasible methods to get unexpected results from the opinions of the subjects. This is particularly advantageous in exploratory phases of the research, as suggestions, given by the subjects, enable the further orientation or adaptation of the research questions. Those personal suggestions occur further within structured interviews, but they are more likely to happen within semi-structured interviews because of an informal character of the questioning, the interviewee feels more invited to explain their thoughts, e.g. Colombo-Technique. However, a major strength of structured interviews results from comparability through uniform questioning. Consequently, this research utilizes a two-phases interview method starting with an informal introduction so that the interviewee and the interviewer can find a trustworthy level and afterwards merging into the second phase of structured interview questions. Furthermore, qualitative expert surveys with professionals offer the researcher insider knowledge towards the contexts and interrelations within the research field.

Interviews require a precise preparation of the questions or the interview guide. In addition, the location, date of the interview, as well as the invitation to the interviewee must be organized. Furthermore, the group of relevant professionals has to be carefully selected as this requires good preparation and background knowledge about the interviewees and their connections toward the research question. In parallel, the questions enclosed within the interview guide must be prepared. This process has to be done carefully to ensure that the quality of the results will not be subjectively influenced by the character of the question style.

These processes are considered to be time-consuming. Another important challenge results from the necessity of acquiring skills in leading an interview. The researcher must be able to actively listen and sensitively engage within the interview-situation. Furthermore, the researcher must flexibly react to the interviewee to ensure a good conversation flow. Moreover, the researcher must be able to have an empathetic but balanced understanding of the viewpoint of the interviewee, without influencing the result of the conversation. Furthermore, the risk of bias occurring within the interaction must be considered. A serious weakness results from the ambiguity of language. Words or content can be misinterpreted by the recipient within the conversation.

The shortcomings of this method have been recognised, but because of the strengths discussed above, this method satisfies the utilization for this research by enabling the understanding of the operator's insight into motivation, fears and subjectively experienced hurdles towards HRC.

3.2.3.3 Focus Groups of Experts from the digitised Industry

Focus Groups (FG) is a traditional qualitative method to reveal the opinions, feelings and attitudes of a small and preselected group of people (Martin and Hanington 2013; Krueger and Casey 2009; Morgan 1996). The research method has been undertaken in Wismar and Rostock in Germany, and also Odense in Denmark. The members of the Expert Group Robotics & AI held by the Chamber of Commerce and Industry in Rostock participated. Questions about how industrial design can satisfy industrial expectations were discussed, and knowledge about the future of robotics, especially the HRC was shared. Four FGs were completed respectively on 18th of June, 04th of October and 21st November in 2018 and 03rd/04th April 2019. This method achieved further insights into design-related questions such as: Does there exist any underlying emotion when working with a robot? Do change requests for the workplace design concerning the HRC exist? It is generally advisable to supplement the FG-method with other qualitative or quantitative methods. This is helpful to compare and evaluate the respective results that are answering the same research questions.

Strength and weakness of Focus Groups

In a well-moderated FG session, the participants feel safe and equal within the group dynamic and are likely to share their opinions and views. The particular advantage of this method results on one hand from the diversity of the insights and on the other hand the possibility to derive a pattern of high importance from recurring elements.

Good mediation skills are needed to moderate FGs. Researchers leading FGs must be actively prompting the dynamic of the session as well as be able to empathetically understand the group dynamic. This is particularly important to be able to react towards over-talking as well as if someone feels insecure or anxious within the group to react with additional support. An additional weakness of this method results from high time consumption for preparation of the sessions, e.g. the invitation of appropriate members towards the research field, the organisation of a date and place to set up the FG meeting, the preparation of materials as presentation slides and questionnaire guides. Furthermore, careful attention must be paid to avoid bias. Similar to the interview method, influencing of the group can falsify the results of the session.

Besides the awareness of the weaknesses as mentioned above, FG sessions offer an effective way to gain insights into a broad variety of opinions and ideas to answer the questions of this research.

3.2.3.4 Behavioural Mapping

Behavioural mapping is classified as an observational, explorative and qualitative approach (Martin and Hanington 2013; Sommer and Sommer 2002). In order to examine the cooperation between the operator and robot and defining the boundary of the area that the operator can achieve; a workbench was set up within the laboratory. The method helps to track the subject's upper limb dimensions and operator's movements when solving manual tasks related to the work field of industrial montage.

Strength and weakness of Behavioural Mapping

Behavioural Mapping offers an effective way of indicating the subject's location-based, specific behaviour. It enables repeatable observation due to its execution within controllable environments under verifiable conditions. The major strength, concerning this research, results from its value for the identification of specific dimensions for future applications in workplace design.

The pitfall of this method has been recognised as influences from the perceived observation that changes the subject's behaviour. Especially within a laboratory set-up as in an unfamiliar environment, nervousness can occur and affect the behaviour of the subject. Furthermore, this method suffers from the fact that the reasons for the behaviour remain unclear.

Gripping and operation areas of 10 participants, students of the Hochschule Wismar, have been detected utilizing a birds-eye camera. No data of the participants was stored since the main reason for this method was to help the author to understand the individual's spatial behaviour and preferred operation areas. The method was utilized within the laboratory work-environment set at the Production Technology Laboratory, Hochschule Wismar, University of Applied Sciences: Technology, Business and Design.

3.2.3.5 A controlled experimental Project

This design-orientated research benefits from a controlled experimental project to physically evaluate an ideal concept/prototype of workplace design designed by the author. The prototype is part of the participatory design process and was employed throughout this research and research data being used within each specific phase.

Prototypes are widely utilized within design research (Wensveen and Matthews 2015; Houde and Hill 1997; Lidwell et al. 2003). They are differentiated related to their elaboration accuracy. So-called low-fi prototypes such as concept sketches and mood boards are usually employed in the early phase of the NPD (new product development), whereas the Hi-Fi-Prototypes enable interaction within a digital prototype model, physical model and/or a model that already contains implemented and (partly-) functioning interfaces (Martin and Hanington 2013). In this research, the author developed practically a laboratory prototype which was classified as a Hi-Fi model, but with some limitations due to lack of technology resources, costs and time constraints.

Strength and weakness of prototype-based, controlled experiments

A prototype offers the opportunity to test a system-design in terms of its usability, context integration and level of acceptance. Moreover, iterative prototyping offers the possibility to identify deficiencies of a concept, to seek appropriate countermeasures. During the evaluation participated in by the users, it can be determined if the system works well or requires some amendments. User's view on solutions created by a professional developer/designer/engineer give valuable insights weather the design will fail or succeed/will be accepted. Participatory research involves user within the process in order to receive indications of how to improve the intended solution. In summary, prototyping helps errors to be detected at each stage, therefore allowing the targeted adjustments to avoid/reduce the costs incurred within a project.

The Hi-Fi prototyping can be criticised for its high costs and work time consumption. The method is also restricted as it represents only exemplar models of real-world systems, not including the full context and holistic factors of a system. In addition, prototypes are mostly without holistic functioning due to their model character. Since there is often no possibility to evaluate the prototype within the real-world application field, a laboratory version has been set up which indicates some issues. Laboratory prototyping can be criticised due to discrepancies related to the original environmental conditions.

To overcome the lack of technique, Martin and Hanington (2013), propose an extension of the prototyping method using the *'Technique of the Wizard of OZ'*. Thereby the researcher is simulating parts of the system's behaviour while interacting with the subject. Within this set-up, the subject is not aware that the technical system is controlled by an operator. This technique is well suited to bridge prototype phases, where components of the system are not yet fully evolved and implemented but should be already tested towards their value for the further development of the holistic system. Furthermore, the subject gains the experience of the functioning system. This technique enables the researcher to observe a subject's reactions which are not affected/distracted by the technical lack of the prototype. Successful utilisation within research on HRI has been done by Patel et al. (2006).

The controlled experiment using a prototype is part of the iterative process of this research and was used for evaluation. The evaluation through an experiment was to test the prototype of a conceptual workbench-system through potential users aiming to clarify the users' expectation, acceptance and natural reactions within the HRC. Working with the participant is a significant part of the participatory/iterative design process. This method helps to understand the users' aspiration and evaluating the determination of the proposed design of the prototype.

Due to the highly important quantity and relevance of the controlled experiment, the utilized method, as well as a description of the research design and results, are given separately from the preliminary methods and results. Therefore, the controlled experiment is detailed in Chapter 5.

3.2.3.6 Overview of Methods employed in this Research

A summary of the strengths and weaknesses of the methods that have been used within this research is as follows.

Table 8 - Strength and weaknesses of the utilized method bundle.

	Strengths	**Weaknesses**
Empirical field trips	• empathetic insight into the role of the subjects and the context within an on-site environment • on-site conversations with subjects	• heavy time consumption • short period spends with the subjects • bias, e.g. Rosenthal-effect (Rosenthal and Fode 1963)
Interviews with stakeholders/ targeted users	• direct insights towards experience, perception and opinions of the subjects • ability to receive unexpected opinions of the subjects	• high time consumption for preparation • necessity of communication skills leading an interview • ambiguity of language can lead to misunderstandings

Focus Groups	• effectively reveal the opinions, feelings and attitudes of the participants • high range of diverse insights given within one session	• good mediation and moderation skills are paramount • high time consumption for preparation of the sessions • risk of bias
Behavioural Mapping	• repeatable observation due to controllable conditions • identification of specific dimensions for future applications in workplace design	• reasons for behaviour remain unclear • influences as the laboratory environment or the presence of the researcher may affect the subject's behaviour
Controlled experimental project	• identification of deficiencies enables one to take appropriate countermeasures • participatory process involves end-user	• high development and work time consumption • high expensive Hi-Fi-Prototyping • model-character of real real-world systems

Another limitation that must be considered for each method mentioned separately is that ethical approval must be obtained before conducting the study.

Besides the theoretical analysis phase including literature evaluation, creative techniques like fast visualisation, mind-mapping and visual organising of elements within mood-boards have been further utilized to understand processes and issues of the research field. Based on the findings of the empirical field trips, behavioural mapping, survey of industry and interviews, as well as based on results from FG sessions as discussed in this chapter, a scenario has been developed and transferred into a design-concept of a workplace system for HRC, which in turn was set up as 1:1 prototype to measure strain-relief of subjects and their acceptance towards HRC within an evaluation experiment.

3.3 Summary of Chapter 3

This research utilizes the Double Diamond Design Process by applying a mixture of qualitative and quantitative research methods related to HCD aspects. The method bundle aims to evaluate issues of the digitised industry, as well as gain knowledge of how to support operators within the digitised industry especially working with autonomous machines, e.g. HRC. Therefore, the assortment of the methods bundle has been carefully selected due to their relevance towards effectively and appropriately answering the research questions.

Chapter 4. Preliminary Results and Pilot Analysis

This chapter outlines research findings from the secondary research, field trips, interviews, FG and behavioural mapping, and have been analysed accordingly.

4.1 Empirical field trips to the Industry

Field trips have been made to several production plants to investigate current workplace environments and existing conditions.

To clarify issues of existing workplaces within digitised industry, field trips are part of the first phase of this research framework. The first phase is characterised as a phase of divergence. Therefore, the researcher must concentrate on keeping his/her focus of attention also open for unexpected findings or new arising research questions.

Bfore conducting field studies, relevant companies were identified that are related to the aerospace supply industry and/or apply robotics. Relevant companies were identified through participation and discussions at conferences, as well as through the network of the Hochschule Wismar, University of Applied Sciences Technology, Business and Design, and the Group of Experts from the Robotics and AI industry, Chamber of Industry and Commerce IHK in Rostock.

A combination of national and international companies of different sizes and with different focuses in their fields of work was selected. In addition to research institutes, companies from the manufacturing industry were contacted, informed about the purpose and aim of this research work and asked for permission to visit the development/production facilities.

In addition to all organisational arrangements, a presentation of the research objectives have been prepared. In the case of the Aero-Coating GmbH the presentation was send to the doorkeeper to inform about the goals and needs of the study and to apply for permission to visit the company and its employees.

At the day of the field trip the researcher started with giving a short introduction of her position and her mission. In many cases it was even possible to give a digital presentation on-site. Often the companies' representative also gave a short presentation of the company and current development projects.

Afterwards, the facilities of the companies have been visited. In most cases it was possible to visit the production plant and watch the employees working under real-world circumstances. Often, cooperation with joint-arm-robots has been part of the production plant. At the research institutes the laboratories where studies with robots where conducted have been visited.

While visiting these facilities the researcher actively collected impressions of the workplace environments and conditions. If permitted the research made videos or took photos to collect interesting artefacts and impressions. In cases where it was not possible to take photos or make videos of the workplace conditions, the research took notes to record the experienced impressions. If possible, the research talked to the representatives but also talked with the operators/employees working with the robots, to collect some insights and experiences towards the HRC. After the field trips the researcher compared the photos, notes and videos to find patterns of issues.

This following section concentrates on the outcomes obtained from the automated industry and presents the backgrounds and facilities of those companies visited. Field trips and interviews were conducted on-site of the following companies/organisations.

4.1.1 Research undertaken in Odense Robotics Cluster Denmark

A field trip has been made to the Danish Cluster for robotics and automation in Odense Denmark between 03rd/04th April 2019. Similar to the silicon valley in the US, this cluster unites 133 companies who share the vision that robots meaningfully change workplaces (Odense Robotics 2020). Mikkel Christoffersen, a Business Manager at Odense Robotics showed the author around the Odense Robotics Start-Up Hub, an incubator that fosters innovative developments within the field of robotics and automation. The start-up hub not only facilitates developments of industrial joint-arm-robots but also robots like the Paro[22] and Nao Robot[23] are also explored to investigate HMI. Besides this, visits to companies within this rising community have been undertaken as follows.

- **Mobile Industrial Robots A/P**

The company is a leading manufacturer of autonomous and mobile robot units. The robot units are assembled, programmed, and continuously developed at the headquarters with the accompanying montage plant, located at Odense. The mobile units are utilized for the internal material transfer of cargo boxes. The robotic modules are varying by maximum load capacity

[22] Paro the therapeutic seal-like robot is utilized to help people suffering from cognitive disorders like dementia or Alzheimer’s (Chang et al. 2013).

[23] Nao Robot is a humanoid robot which is used for research on HMI, e.g. investigations on children with autism social engagement in interaction with Nao (Tapus et al. 2012).

rising from 100 kg to maximum 1000 kg. Furthermore, the modules are moving safely within production halls and utilizing coloured light ribbons for indicating the changing status of the AGV. In addition, the AGVs can be integrated into the existing manufacturing structures in an agile manner due to customized application solutions offered by the company. A presentation of the company as well as a guided tour through the testing areas for the module development was given by a representative of the company.

- **Universal Robots A/S**

Universal Robots A/S is a manufacturer of industrial joint-arm robots for integration in hybrid human-robot workplaces. At the headquarters a presentation of the company profile, the product palette, as well as a guided tour through the assembling hall which is closely connected to the headquarters, was given by Richa Hallundbæk Misri, Robotics Business Consultant and Co-Founder at REInvest Robotics. Considerable insights into shared work environments have been gained through the visit to the montage hall, where operators are assembling the parts of the joint-arm-robots in cooperation with precursors of those industrial robots.

- **Gibotech A/S**

Gibotech A/S provides solutions for systems connecting automation of machines and robotics for the application fields industry and hospitals. Joint-arm-robots for direct cooperation with operators are not the focus of Gibotech A/S service palette, but industrial joint-arm-robots with the ability to lift heavy weights as well as the integration of joint-arm-robots for small weight samples, as well as automated solutions like CNC processing and mobile AGVs are their speciality. A presentation of the company and a guided tour through the testing and development areas within the headquarters was given by a representative of the company.

Field trips to companies, not associated with the Odense Cluster have been undertaken in Germany as follows.

4.1.2 Studies conducted in German Industries and Organisations

- **Franka Emika GmbH**

The manufacturer of high-sensitive joint-arm-robots for the integration of shared hybrid human-robot workplaces is based in Munich, Germany. The company Franka Emika GmbH issues an annual invitation to visit the headquarters on their Open Days. In 2018 the manufacturer was visited to investigate the possibilities given by the innovative introduction of the Panda robot. The Panda can be integrated into the plant without a safety cage, as torque sensors in all seven axes enable rapid detection of undesired collisions, so that safe interaction is ensured. Furthermore, the lightweight joint-arm-robot excels through the hand-guided programming mode which enables easy and intuitive programming of tasks. Moreover, the robot uses changing colour lights to indicate its current status from programming modus to running the program and error modus, which reduces irritations while working with the robotic system. Through the visit, insights into the range of possible utilization scenarios as well as insights into the functionality of the new kind of robots for collaboration was gained. The handling of the robot and user-friendliness of its programming system was tested on-site.

- **Fraunhofer IFAM**

The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM is working on research and development of systems within the industrial value chain. Dr Dirk Niermann, Head of Department Automation and Production Technology, gave a presentation of the research field related to robotics and automation for utilization within the production and maintenance processes of large-format, complex component structures, like those used in aircraft construction. The research institute is based in Stade, Germany. On-site, Dr Niermann gave a guided tour through the development hall of the institute, containing heavy weight lifting joint-arm-robots and AGVs.

- **Mebak Metallbau GmbH**

The system supplier Mebak Metallbau GmbH is located in Schönberg, Germany and is processing several types of metal for a diverse range of areas of applications, e.g. construction for the office furniture industry, shopfitting and medical technology sector. Furthermore, the workshop of the company provides partially automated systems to produce components for general as well as specialised machine constructions. Managing director Ronny Freitag gave a presentation of the product range of the company. Afterwards, he gave a guided tour through the production plant on site.

In sum, all of these field trips undertaken, have been enabled by companies trying to positively develop the workplace environments for the better, for their employees. All production halls visited are characterized by a particularly clean working environment with little noise and dust, which further meet a high level of safety. In sum, the field trips have been a chance to gain a comprehensive overview of existing issues and potential within the field.

Another pro-active company is the aerospace supplier Aero-Coating GmbH. Considerable insight has been gained working in cooperation with the company located at Wismar. To support research to improve hybrid human-machine workplaces, the company made one of their production processes available as a real-world-scenario for the development of this thesis pilot prototype Chapter 5 A controlled experimental Project. To get to know the process and conditions, those were discussed on-site during an analysis of the workshops.

- **Aero-Coating GmbH**

Field trips have been conducted at Aero-Coating GmbH, a supplier for the aviation industry. The manufacturer coats components made of metallic or polymeric materials with functional coatings against corrosion and uses a joint-arm-robot to spray-paint the metal parts. Within a visit to the company's production plant, insights into the interaction between operator and robots have been collected.

At this point, components are separated and sorted into corresponding holders for the transfer to the robot for further processing. A conveyor belt transports the containers to the paint shop cabin. A fence separates the workspace of the operators from that of the robot. In addition, safety light barriers secure the paint shop to prevent unauthorized trespassing. If an employee opens the door to the robot, it stops its activity immediately.

The following description of the pigmentation process of threads of screws is given by the company for utilizing within this thesis.

Pigmentation by a lacquer-robot

1) Batching

Components for thread coating of screws are provided on the parking space after the incoming goods inspection. The operator checks the parts according to the given specification requirements. Then, appropriate masking rails are selected also according to given specifications. Corresponding masking rails are taken from the rail carriages. Components for thread coating are batched by employees according to requirements given. From a component size of 5mm, shading can occur due to the bridges within the form of the masking rails. To avoid shadowing, the slots next to the webs of the rails cannot be filled. After the components for thread coating have been batched, the stocked masking rails have to be placed by hand onto the conveyor belt which then carries the rails into the machine cabin. The masking rails are recognized by the paint-shop system and the processing parameters are set automatically. The masking rail is then picked up by the gripper of a horizontal conveyor and then inserted into the spray paint cabin.

2) Spray painting

Afterwards, the painting of the components is carried out through the robotic system automatically according to the stored processing parameters. After painting, the masking rail is placed on the conveyor belt which carries them to the outlet.

3) Pre-Drying

The deposited masking rails are pre-dried within the evaporation area. For this purpose, the masking rails are carried via a conveyor belt through an air stream. After pre-drying, the masking rails are removed manually from the conveyor belt. On the charging table, the masking rails are carefully removed onto a baking tray.

4) Backing

The coated screws are being placed on a tray which is then manually carried and placed into an industrial oven. There the components are going to be further processed.

Figure 29 shows operators who are working on the batching task: a real-world problem for application within controlled experiment Chapter 5.

Figure 29 - Operator at the manual manufacturing workplace. Source: Aero-Coating GmbH.

4.1.3 Findings from the field trips

Findings indicate that the current environment of industrial workplaces is very different from office circumstances.

The findings expose issues within existing industrial workplace environments and the challenges of design. The following critical points are identified re the HF’s physical, cognitive and organisational limitations, that was observed by the author/suggested by the operators:

1. A highly repetitive character of working tasks or, in contrast, high load due to continuous activation while monitoring processes
2. Cognitive strain due to a wide range of warning lights and information signals e.g. using wearable electronic devices, monitoring displays
3. Visual disturbance and restriction of movement space due to tools, devices and workpieces stored within the working area
4. Long walking distances to storage locations and machines result in physical strain and high travel time consumption
5. High physical fitness requirement when manoeuvring large components, but at the same time high motor skills required when sorting or assembling small parts
6. Individual adaptation to the physical dimensions of the operator is not given. A changing of posture during the working hours is not possible (standing or sitting workplaces)
7. Design of table surface often does not follow ergonomic design guidelines, e.g. reflectance of the material, shape, and dimensions
8. Incorrect lighting and noise negatively affect the health and well-being of the operators
9. Individual lighting adjustment is not yet integrated
10. Real HRC is not yet implemented – Robots are often working separately from the operator's task
11. Within line-production, one robotic system is often used next to the actual work area of the operator and consequently is parallel utilized by a maximum of two operators as follows:
    - One operator – two robots
    - One operator – one robot
    - One robot – two operators.
12. Need to promote communication with co-operators; Coordination about joint work progress, interpersonal adaptation through shared working spaces. People cannot communicate with each other producing in series.

13. Lack of adequate integration of interfaces for HMI: Conventional input and output devices for controlling the robot, for controlling the machines, and monitoring the system take up a lot of space around the workplace
14. While interacting with robots, the operator is not able to foresee the direction of movement of the autonomous operating machines, e.g. AGVs, robots which leads to irritation, low acceptance up to anxiety behaviour
15. Adaptation of the workbench system to spatial behaviour characteristics is not yet regarded
16. Strain caused by time pressure and timing of breaks

Empirical field trips on-site at production and assembly plants, and research institutes within the field of digitised industry, automation, and robotics, provided reliable insights into the potential future of workplace systems for HRC. Consequently, the next section expands the preliminary results by giving details about the procedure and findings of the survey and interviews.

4.2 Survey and Interviews

A two-part series of interviews were carried out to empathise with the operators and stakeholders from manufacturing and production sectors, together with professionals and researchers within the digitised industry, aiming to receive an in-depth insight into the HF needs. Interviewees consist of both experts and extreme-users from manufacturing and pertinent industries with different questions. Questions were developed based on issues identified in the literature reviews chapter, in terms of underlying reasons for behaviour/interaction within the workplace, acceptance of HRC and workplace design. For example, interviewees with design or engineering backgrounds were asked about their expectations of the future role of design which was discussed in Section 2.5.2 The contemporary Role of Industrial Design.

Interviews have been undertaken in two languages: German and English, with international and regional interviewees. The interview series was supported by an interview guide (see the interview guide in Appendix C) and was structured into the following categories:

- Interviews with experts, e.g. professionals, researchers from the field of robotics, digitization and/or product design (structured, semi-structured)
- Interviews with operators (unstructured)

The experts have been asked via telephone to answer structured questions. Afterwards, a summary of the conversation has been sent to the interviewee for review and approval.

4.2.1 Interviews with Authorities and Design/ Engineering Practitioners from the Industry

1) Interviewee Dr Elias Knubben, Festo AG & Co. KG

The industrial partner FESTO supported valuable insights within an interview. As an innovation leader, the company FESTO offers automation solutions with electrical and pneumatic technology in factory and process automation. Dr Elias Knubben, Head of Research and Innovation, Senior Vice President at Festo has been asked to talk about future requirements and latest innovations in the automation industry concerning HRC. Knubben affirms that operators, robots, and autonomous machines will increasingly share identical workspaces and highlights the importance of a flexible working space, which meets the requirements of the digitised industry to support the operator. He highlights that people gain an understanding of positive effects through the integration of a robot within their work environment if the robot supports them within undesired task solutions. Consequently, people feel promoted through the robot colleague and do not feel replaced by the machine (see full interviews in Appendix B).

2) Interviewee Dipl.-Psych. David Kremer, Fraunhofer IAO

Comparable points to the opinion of Knubben were made by David Kremer, competence manager at Fraunhofer IAO. Kremer illustrates how acceptance towards the robotic system arises if the robot remarkably supports the working tasks for example by taking over ergonomically exhausting or inappropriate work tasks. Further, he affirms that the major hurdles for the integration of HRC result from operator’s perception of the robot colleague. According to Kremer’s investigations, the robot’s physical proximity is often perceived as unpleasant or frightening.

Additionally, he draws attention to another hindrance for successful integration. He highlights the importance of an adequate workplace design which is challenged by complex elaboration factors like safety standards, construction, ergonomics et cetera but also lists, that a successful workplace system must be able to constantly adapt to volatile working environments and technology developments (see full interviews in Appendix B).

3) Interviewee Dipl.-Des. Andreas Hackbarth

The industrial designer Andreas Hackbarth enriched this present research by supporting highly valuable insights into the changes the design sector has gone through and challenges design is currently influenced by. He draws attention to various disruptive factors popping up which nobody from product management might have on their radar, e.g. pandemics like corona virus or worldwide conflicts. Accordingly, Hackbarth postulates the possibility to adjust established methods from engineering and design to the real-world requirements of the reality and give his opinion of how consequently the training of design students should be adapted to the changing demands (see full interviews in Appendix B).

Besides the structured interviews as mentioned above, unstructured interviews have been undertaken as follows.

4.2.2 On-Site Interviews

On-site interviews were conducted during the following visits, the author was able to talk to representatives/operators at the assembly lines and maintenance desks within the industrial plant, and asked questions regarding the HRC and its future.

- Aero-Coating GmbH
- Start-up Hub Odense
- Mobile Industrial Robots A/S
- Universal Robots A/S
- Gibotech A/D
- Mebak Metallbau GmbH
- Franka Emika GmbH
- Fraunhofer IFAM

4.2.3 Interviews at Conferences

Interviews with representatives from industries have been undertaken over a number of national and international conferences. Knowledge/questions re the future of HRC were discussed.

Conferences where the author was invited for a presentation.

- Regiopolregion Rostock, 2017
- 3rd International Conference on Design & Production Engineering, 2018

- Liverpool John Moores University. Research Faculty Week 2018, 2019
- IEEE International Interdisciplinary PhD Workshop, 2019
- Schweriner Wissenschaftswoche, 2019

Conferences attended without presentation:

- Autsym, 2017
- Technologiekonferenz MV. Strategierat, 2018
- Wirtschaftskonferenz Schwerin IHK, 2018
- ZAL Innovation Days, 2019
- Nørd. Digital MV, 2019

Furthermore, the author has been offered opportunities to present her research findings that focus on the challenges and opportunities of the HRC in the following companies:

- Lufthansa Technik AG
- Airbus

4.2.4 Results from Survey and Interviews

Within the following, the derivation of the major challenges and potentials identified through the interviews are listed:

Table 9 - Challenges and potentials of workplaces for HRC derived from interviews.

Issues	**Analysis**
Operator complains of ambivalent feelings towards robot colleagues.	Operator's acceptance towards HRC results from perceived assistance advantage through the robot.
Complex elaborate set-up of a shared workplace for HRC is perceived as one major hindrance.	Design guidelines and best practice examples support the increase of HRC workplaces.
The ability of workplace systems must be able to adapt to constantly	Importance of flexible, modular and scalable working spaces constantly adapts to volatile conditions.

changing requirements of future working environment.	
Operator needs are often not sufficiently regarded, which results in low system acceptance or workarounds.	Successful integration of hybrid human-robot workplaces is empowered through regarding of HF within a participatory process.
The rising complexity of design challenges requires a broad base of knowledge within diverse fields for system development.	Interdisciplinary teams are sharing and evolving knowledge and receiving solutions to be able to answer future challenges.

The following section details the research design of the FG sessions and presents findings.

4.3 Focus Groups of Experts from the Robotics and AI industry

4.3.1 Focus Groups of experts jointly organized by the Chamber of Commerce and Industry in Rostock

Entrepreneurs and scientists from the robotics and AI industries participated in four FG meetings which were organised jointly by the Chamber of Industry and Commerce IHK in Rostock on 18th June, 04th October and 21st November in 2018, and 03rd/04th April in 2019.

- **Focus group of experts conducted on 18th June 2018**

The Fraunhofer Institute for Computer Graphics Research IGD hosted the first meeting of this expert group. After an introduction of all participants attended, a presentation of the research fields at the Fraunhofer Institute for Large Structures in Production Engineering IGP and Fraunhofer IGD was given. At the meeting, the future of robotics in north Germany, more precisely Mecklenburg-West Pomerania was discussed. As a contribution to answering this research's questions, the following statement is important as it summarises an outcome of the session. The group's stakeholders agreed that the country's existing interdisciplinary skills have to be connected. In addition, the involvement of small and medium-sized companies is particularly important in order to successfully orientate the development and alignment of robotic systems to real-world problems.

- **Focus group of experts conducted on 04th October 2018**

The meeting of the expert group was hosted by the company PLANET artificial intelligence GmbH, Rostock. Within the 2nd meeting of the expert group, an FG session was set up. After a presentation of the research study, the individual members of economic institutions and research institutions were asked about their experiences towards the interaction of robots working close to operators within an unstructured part of the session. Furthermore, the participants were asked to give feedback on their opinion about robotics and its integration within the research and business environment in the region of Mecklenburg-West Pomerania.

Afterwards, the participants (n=10) were asked to complete a questionnaire (see Appendix C: Interview Guide).

Figure 30 illustrates the high diversity of the background of the FGs participants.

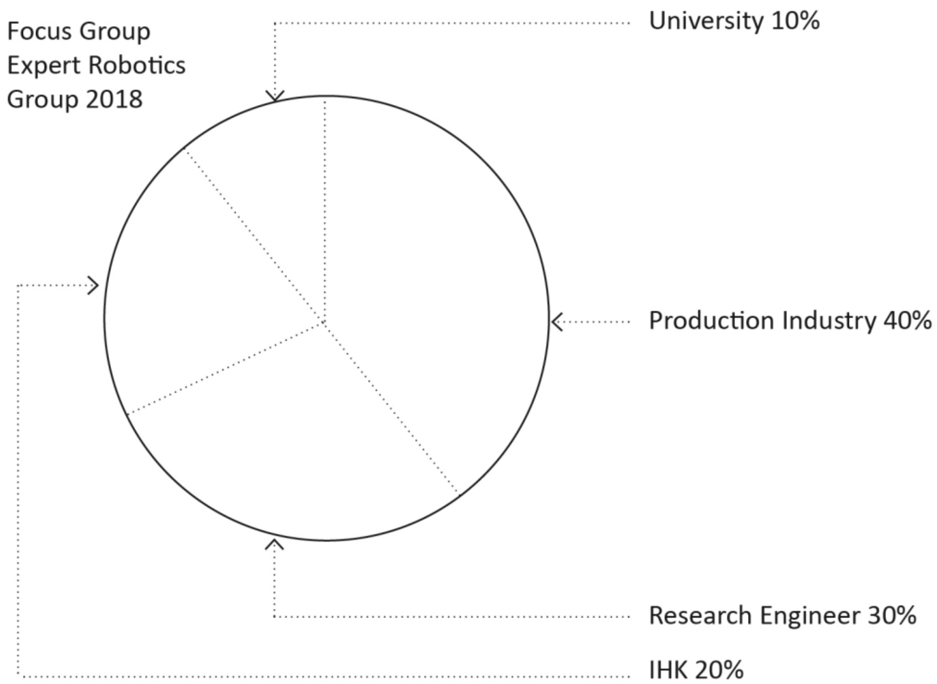


Figure 30 - Background of FG participants. Expert Robotics Group October 2018.

Reporting results from the evaluation of the FG session, the following findings were gained:

1. Almost all participants commented that in the future flexible management of personnel capacity is particularly important (7/9)
2. When the subject was asked about the role of the human work on the shop floors of their company, the majority of respondents estimate future significance as high to very high (7/7)

3. All participants agree that the character of HMI will change generally (10/10)

- When the experts were asked about the most significant changes they expect in HMI, the majority commented that robots will positively affect the work of the future e.g.
  - Cooperative assistance systems
  - Knowledge-transfer from person to machine
  - Robot as a workmate

- **Focus group of experts conducted on 21st November 2018**

Hosted by the Hochschule Wismar, University of Applied Sciences Technology, Business and Design, the meeting started with a presentation of this research's objectives and approaches, followed by an open discussion about the research field. The participants of the meeting were representatives of politics, including the German Ministry of Energy, Infrastructure and Digitization and the Chamber of Commerce and Industry, Rostock, as well as representatives of various scientific research institutions, universities, and representatives from small and mid-large companies from the industrial production sector.

- **Focus group of experts conducted on 03rd-04th April 2019**

Supported by the Enterprise Europe Network and the Chamber of Commerce and Industry, Rostock, a delegation was sent to visit the Odense Robotics Cluster, Denmark as detailed in Section 4.1 Empirical field trips to the Industry. During the visits to the robotic and AI-related companies, discussion and exchange of ideas towards the future development of the robotic sector were sought.

4.3.2 Results from the Focus Groups

The FGs coincided with the previous studies that underpin the following conclusions:

1. Robotics is crucial in the future, therefore the cooperation between humans and robots needs to be supported.
2. Human-friendly systems need to be considered, therefore the research into developing/evaluating the proper systems is essential.

The section expands the results into analysis of anthropometric requirements. The study focuses on understanding of individual's preferences and variations, such as gripping and operating behaviour. The Behavioural Mapping method contributed findings as follows.

4.4 Behavioural Mapping

Within the laboratory set-up at Hochschule Wismar, individuals' areas for reaching and operating have been examined as follows.

The subjects were asked to sit down at a worktable at the laboratory. Then the subjects were asked to take a masking rail from a given removal zone. Afterwards, the subjects were asked to take a box filled with screws from a specified removal zone. Finally, the subjects were asked to fill the screws into the holes in the masking rail and to place them on any location on top of the surface of the table they would think is suitable as output zone. The sequence of the task was based on the process flow of charging at the manufacturer Aero-Coating GmbH in order to establish a connection of the experiment to a real-world scenario (see Chapter 5. A controlled experiment: Demonstrator).

The subjects were students from the Hochschule Wismar, University of Applied Sciences: Technology, Business and Design and the methodological examination were carried out to accompany the laboratory experiment described in Chapter 5.

A camera was attached to the ceiling of the room so that the worktable could be seen from a bird's eye view. The images of the camera were evaluated using an image recognition program: The Open Pose algorithm, an open-source project, was used to detect human movements and dimensions. Figure 31 illustrates how the software detects and visualizes the nodes of the skeletal structure and body dimensions by different colours.

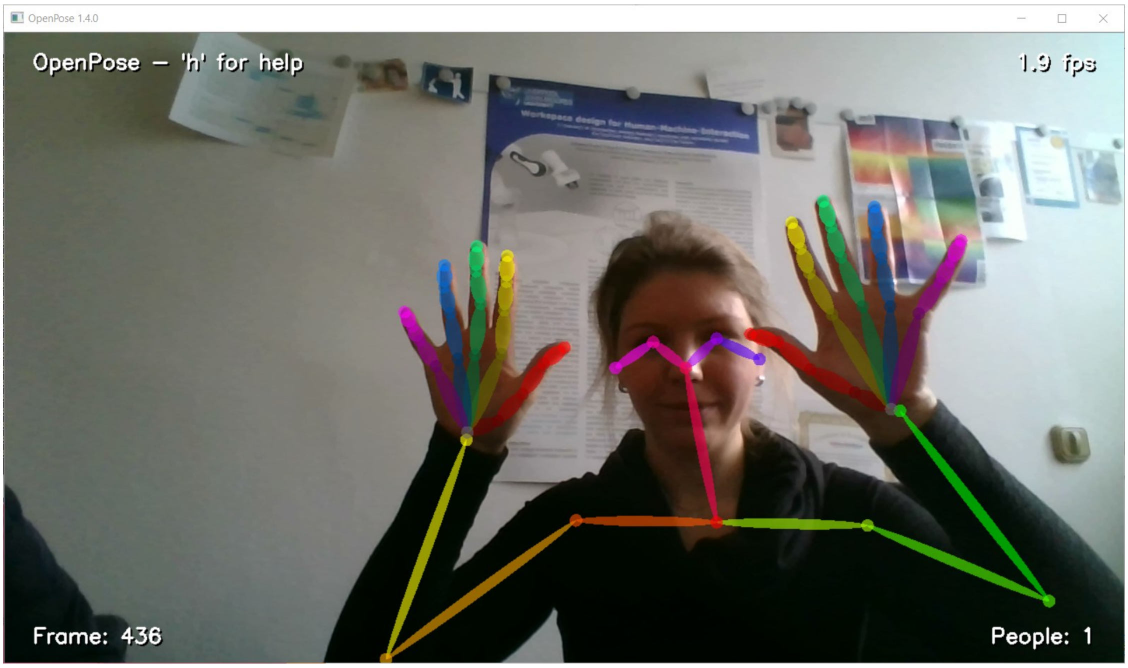


Figure 31 - Visualisation of the identified body parts by utilization of the Open-Pose Demo Program.

Figure 32 example shows the differences in the individual's preferred gripping and operating areas. The tracking of the upper limbs shows varying areas for specific tasks, e.g. assembly, examination, storage and output zones, but also highlights the differences resulting from the individual's preferences as well as differences resulting from body conditions.

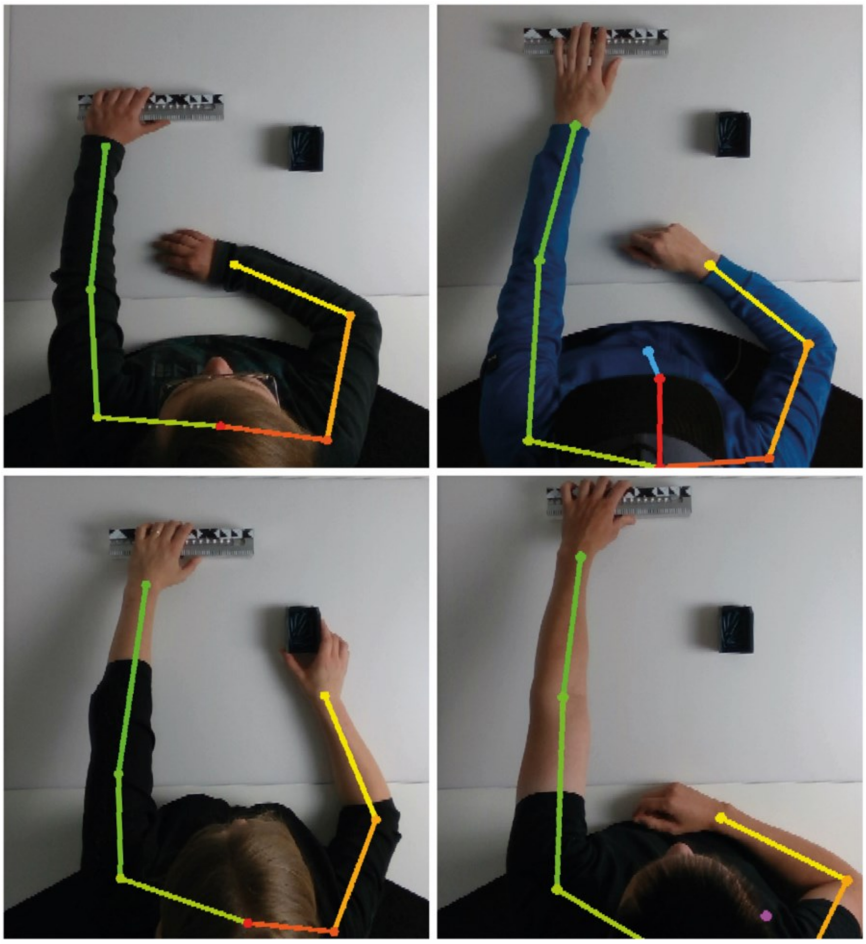


Figure 32- Bird-eye view while behavioural mapping shows significant differences in gripping and operating areas of several people.

Mr Daniel Luthardt practically contributed with the technical set up, e.g. the installation of the camera system and integration of the Open Pose Algorithm. The task was given to him by the author who supervised his work during the course of the project. The ideation, the concept, organisation and carrying out the experiment, and evaluation has been done by the author.

Results from Behavioural Mapping

The gripping and operating areas vary from individual dimensions and posture (see Section 2.1.1 Physiological Limitations). This experiment shows the areas that are affected by individual/specific behaviour. Subjects with comparable dimensions of body parts clarified individual-preferred zones for taking and exchanging workpieces, which needs to be considered within the assisting systems. The following aspects in supporting individual gripping/operating areas have to be considered when designing workplace systems:

- anthropometrical dimensions of the limbs
- support of dynamic shifting among various body postures
- left or right-handed operators
- individual preferences
- temporary behaviour variances e.g. changes due to injury or tensions

Further study will be conducted to evaluate a prototype in the real-world industrial environment. Repeating this experiment under real-world conditions will improve the prototype over the iterative development process. Furthermore, the larger group of participants will receive reliable data.

The results of the methods utilized lead to a compilation of requirements on workplace system design. Based on the requirements detected, recommendations for future workplace/system design are derived as described and discussed within the following section.

4.5 Pilot Analysis and Discussion

Accompanying the theoretical studies in the literature reviews, through the application of those practical methods described above, the author has established understanding in terms of the environments, current conditions and issues of workplace within the industry e.g. the physiological, psychological and organisational strain, design challenges and potential solutions while working with autonomously acting machines.

The results of Chapter 4 revealed challenges resulting from workplace conditions that are generalized within the following:

Findings	**Analysis**
Psychological strain	
Psychological strain results from extensive utilization/ range of warning lights and information signals e.g. using wearable electronic devices, monitoring displays.	Due to a high number of complex signals and information delivered through communication tools the resulting cognitive load leads to the risk of important information not being perceived or processed adequately.

Operators are visually disturbed by tools, devices and workpieces that are not needed for the specific task solving but stored within the working area.	Visual/cognitive load due to the positioning of objects and displays at the operator's workplace increases the risk of missing or misinterpreting task- or safety-related information. Rapid information processing is particularly important in security-critical areas.
Operators are frequently forced to deal with a highly repetitive character of working tasks and suffer from strain due to continuous activation within monitoring processes.	Fatigue due to highly repetitive tasks solving/ extensive monitoring increases the risk of human error. Therefore, the design and planning of working tasks must fit the psychological requirements of the operator by offering a diversity of working tasks/ assistive systems while monitoring processes.
Operators are negatively impacted by time pressure and pause timing.	System Design that is not regarding the varying requirements by offering options to flexible pause and task solving is putting pressure on the operator that leads to psychological strain.
While interacting with robots, the operator is not able to foresee the direction of movement of the autonomous operating machines, e.g. AGVs/robots which lead to irritation, low acceptance up to anxiety behaviour.	If movements/ reactions of autonomously operating machines are not meeting the expectations of the operator, this leads to high psychological strain/ stress that consequently hinders the successful integration of HRC.
Operator shows ambivalent feelings towards robot colleagues.	Operators show low acceptance if HMI does not support the expectations of the operator. However, an operator's acceptance towards HRC results from perceived assistance advantage through the robot.

Physiological strain	
Operator movements are restricted due to tools, devices and workpieces stored within the working area.	Storage of tools, devices and workpieces within the working area leads to physiological strain and inefficiency due to restrictions of movements.
Devices of controlling robots, machines and monitoring systems occupies massive space within the workplace.	Lack of space for HMI causes the operator's movement to be restricted, and further leads to physiological strain.
Walking long distances between storage locations and machines is time-consuming and impacts operator's physiological endurance.	The infeed and removal procedure of task-related workpieces/tools lowers the system efficiency, moreover, physiologically depletes the operator.
Operators need physiological fitness when handling large components, and also require fine motoric abilities when sorting/assembling small parts.	Heavy physiological strain results from diverse range of required skills ranging from extensive fitness to fine motoric abilities. The system design impacts the quality of support given to solve those requirements.
Dynamic changes of body posture are not supported in working hours. In addition, the adaptation of workbench system to specific behaviour characteristics is not considered, e.g. operator's preference of left or right-hand and temporary behaviour variances due to injury or tensions.	Lack consideration in terms of individual body dimensions and preferences, however it is particularly important for people when sharing working spaces.
Current workbench designs do not satisfy ergonomic expectations, such as reflectance of material, shape and size.	Workplace design physically impacts operators, as poor design will harm their health/wellbeing and leads to a weak performance.

Incorrect lighting, air pollution, vibrations and noise harm operator's health and well-being.	The quality of lighting and air, low noise and vibration prediction are key factors for workplace design. Current design did not consider individual preferences and capabilities.
Organisational strain	
Production line design is not supporting communication between operators.	Operators cannot communicate with each other when working in the production line during the working hours. It's failed in coordination of joint work progress and lacks interconnection with other team members.
Robots usually work in different task from the operators.	Real HRC has not been realised, as Human-Robot Teams cannot work together on the same task.
One production line usually has one robotic system that being placed next to operator's area, hence maximum of two operators may be placed parallel within a production line.	Inefficient use of the robotic system caused by current structure of production system. Therefore, it's inefficient, placing one architecture of robotic system being used by maximum of two operators simultaneously.
Operators can create workarounds themselves if workplace/environment design does not satisfy their expectation. Moreover, operators often feel left out of the NPD process, therefore results in low system acceptance.	An ideal/successful workplace/environment design for hybrid Human-Robot Teams may apply the entire HF principles over the participatory design process.
Rigid systems are slow and expensive in accommodating the demand of fast-changing.	Workplace systems must meet constantly the changing requirements of working-environment. Meanwhile, a flexible, modular and scalable space is paramount in satisfying the volatile conditions.

To answer challenges of today as well as upcoming challenges, the industry agrees that robotics is becoming more and more important, but low acceptance toward Human-Robot Teams and human error due to inadequate system design negatively affects the integration of successful HRI. Therefore, industrial environments require design solutions that regard the value of focussing all dimensions of HF requirements. Workplaces must be seen as holistic environments where all system components are influencing the operator's performance, health and well-being. The results of Chapter 4 revealed the following potentials for HRC:

- Great importance to robotics in the future, explicitly supporting the cooperation between humans and robots.
- Need for human-friendly system has been understood by the industry
- Representatives of politics, industry and research organisations postulate appropriate investigations/developments towards suitable HRC systems

The rising complexity of design challenges requires a broad base of knowledge within diverse fields for system development. Therefore, interdisciplinary teams are sharing and evolving knowledge and receiving solutions to be able to answer future challenges. The rising importance of considering the variety of humans and their varying requirements is paramount to design systems working for a broad range of people.

To give a summary of what can be learnt from the results of this chapter, it can be said that design solutions that follow the one-fits-all-principle do not succeed but also solutions orientating on grouping demands will likely fail. The most potential that can be derived from the results of this methods can be addressed as follows: A dynamic system design that is able to flexibly adapt to the ever-changing requirements and demands of the user features individualisation and therefore will satisfy the widest range of people.

The following section will list what can be learnt from the results of Chapter 4 for future design decisions.

4.6 What Can be Learnt from the Results

The preliminary results and findings discussed in this chapter indicate that the contemporary role of workers within digitised industry is changing. Human and robots/autonomous machines collaboration is getting popular. Therefore workplace/environment design is expected to support and improve workers'/operators' experience, to enhance their performance and reducing/stopping human errors during working hours. Cognitive overload and low acceptance of the HRC appear to be key issues in workplace/environment design. This section will discuss the drives of concept design, in terms of all levels of the HF.

Table 10 - Design-criteria as recommendations derived for assisting workplace systems for HRC.

PHYSIOLOGICAL:

1)	Applying absorbing and low reflection materials to minimise sound/air/light pollutants to protect operator's health.
2)	Providing furniture to support dynamic change of operator's body posture (stand-seat) during their working hours.
3)	Creating a height-adjustable workbench to satisfy operator's individual anthropometric requirements.
4)	Location of input-output zones must meet specific requirements of the operator's behaviour and individual preference.
5)	The shape/size of worktops need to support ergonomically the changes of operator's body posture.
6)	Applying the Biologically Effective Lighting (BEF) to avoid operator's health issues and to enhance their performance.

COGNITIVE:

7)	Reducing repetitive tasks to ensure the operator is sustainably performing better.
8)	Reducing the number of signals to minimise operator's cognitive strain, e.g. removing tools and workpieces unrelated to current task.
9)	Integration of visual guidance systems which indicates the upcoming movement of the robot improves HMI.
10)	Expanding available space by removing/reducing devices on worktops.
11)	Integrating/optimising all functions of devices within the CPS into a single interface to simplify the HMI within the entire workplace/environment.

ORGANISATIONAL:

12)	Separating tool storage/warehouse to simplify the structure of workplace, the AGVs and conveyor belt delivering workpieces, consequently reducing operator’s time and walking distance.
13)	Flexible and scalable modular-structures will adapt the changes in volatile markets.
14)	Shifting from mass production line to matrix production allows more than two operators employing one robot efficiently.
15)	Workplace that encourages communication among operators during working hours, will enhance operator’s problem-solving ability and improve their well-being.
15)	Flexible workplace/environment such as the length of working hours, tasks and multiple choices of positions will reduce operator’s strain and improving their well-being.

Reshaping the robotic system based on the HF

Current lightweight robots are highly sensitive, therefore do not require a fence for safety purposes. As with tools and equipment, the robot is part of a workplace, therefore the robot-controls must fulfil the HF requirements. Collaborative/joint-arm-robots will be interrupted if people enter into their operational area or an abnormal crash was detected. Apparently, this function is important due to security objectives. When people work with a lightweight robot, they feel panicky if the robot’s moving trajectory, calculated by Path-Planning, is extremely close to/crossing directly through their working area. Therefore, operators must undertake obviating actions to avoid unintended contact with robot, so that the robot will not be interrupted and need to shift to the safety mode. Otherwise, operators have to unlock it manually.

Given the discussion above, the interruptions caused by unintended contacts/robot crossing the operator’s working area will lead to irritation during the workflow and low efficiency.

In summary, dynamic adapting individual moving pattern appears to be better. Likewise, the findings postulate that being a part of the workplace, robotic systems must fulfil the HF requirements. Therefore, integrating a self-learning algorithm[24] into the robot controls will predict collision and proactively adapt operator's individual behavioural pattern. Robots must be able to identify/learn individual behaviours/moving patterns to foresee operator's future actions and accordingly adjust its Path-Planning.

4.7 Summary of Chapter 4

This chapter discussed the preliminary research results and possibility of an HRC workplace design. The findings suggest the design criteria of workplace design and drive a concept developed based on the analysis. The following chapter introduces the prototyping of a demonstrator.

[24] Research work related to self-learning algorithm for robot controls is currently conducted at CEA Hochschule Wismar (Kunert and Pawletta 2018; Kunert et al. 2019).

Chapter 5. A controlled experimental Project

A demonstrator is a prototype that simulates a real-world scenario of aircraft material maintenance/manufacturing; it demonstrates a novel/ideal workplace system of digitised factory. This chapter discusses what HCD can help to enhance the performance and usability of an HRC workplace.

- Section 5.1 introduces a prototype of an Assisting-Industrial-Workplace-System (AIWS) for the HRC that presents a model solution created based on the design criteria which were clarified in Section 4.6.
- Section 5.2 lists the components of the laboratory set-ups and implementations of the experiment.
- Meanwhile, in order to define the reliability of the design criteria and assessing the effect within the application scenario, an Objective Workload Detection Method has been detailed in Section 5.3.
- Section 5.4 illustrates how the workload can be significantly relieved by an assisting workplace/environment.

5.1 The Concept of an Assisting-Industrial-Workplace-System for Human-Robot Collaboration

Research outcomes demonstrated in this chapter aimed to fill the gap in creating an HRC workplace to assist Human-Robot Teams and seeking if the HCD method can reduce operator's strain and further enhance their performance. The HF knowledge has been applied in the development of this AIWS for the HRC.

Automated production systems in digitised factories usually consist of machines, tool stores, warehouses and manual workstations. However, this concept extends flexible manufacturing systems into the workplace that assisting hybrid Human-Robot Teams, so as to promote HRC for manual tasks.

As part of the CPS, the AIWS considers physiological, cognitive and organisational requirements of the HF. The concept was designed as a flexible hybrid unit for HRC, preparing industrial production processes to meet the constantly changing requirements of volatile markets.

Figure 33 and Figure 35 illustrate the concept of modular workplace for the HRC as a part of flexible production systems: an assisting component accommodating the HRC workbench to support operators interacting with the digitised production, and delivering timely workpieces/tools that are required for the current task.

A delivery unit has been connected to the AIWS for delivering components and tools, such as the conveyor belt (see the grey arrow with dotted line in Figure 33). The prerequisite of this concept is a networked production system that can assign current work orders to available human resources. Up to three operators can work together with a robot within one unit. The workbench is expandable, so as the star-shape units can be expanded up to five workplaces. A lightweight robot is in the centre to support operators by supplying tools and workpieces that are required by each task.

Traditional devices such as monitors, keyboards and computer mouse are removed. This concept is also adopting worktops as an interface and communicating via gesture. Furthermore, by integrating a post-optimisation/reinforcement learning algorithm into the HRC workplace system will enable the spatial movements of the robot to adapt to the operator's preference.

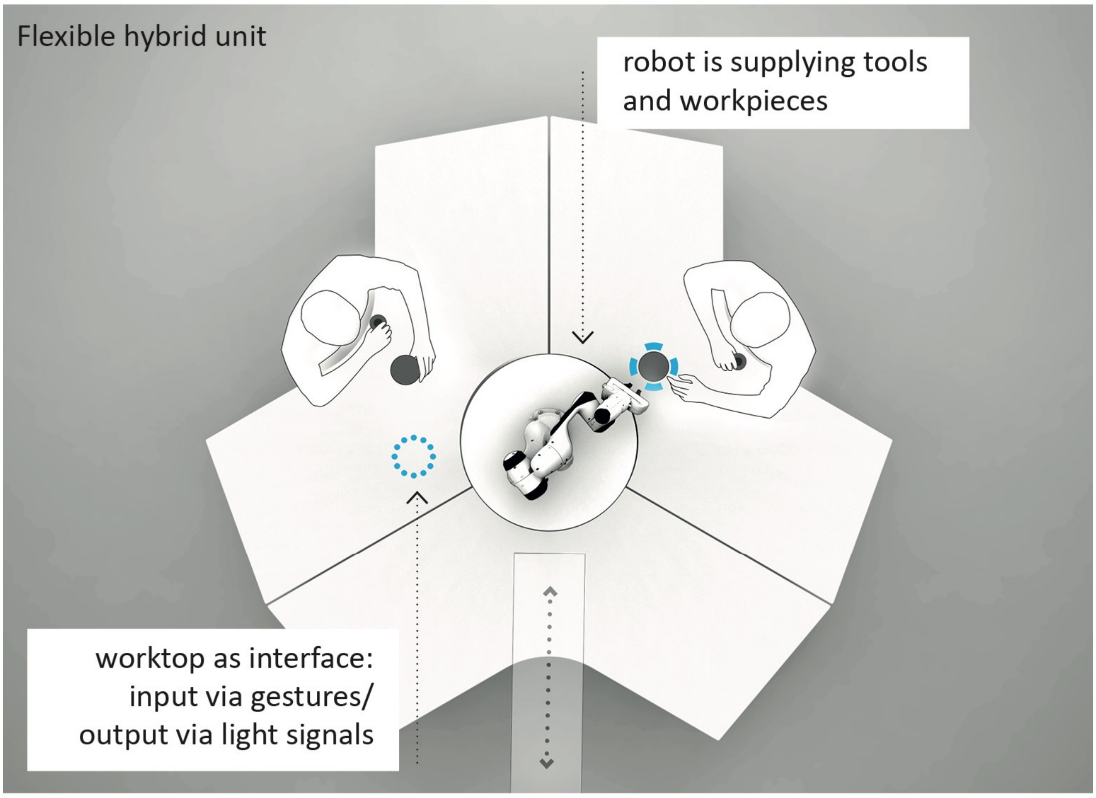


Figure 33 - Concept rendering of the AIWS (1).

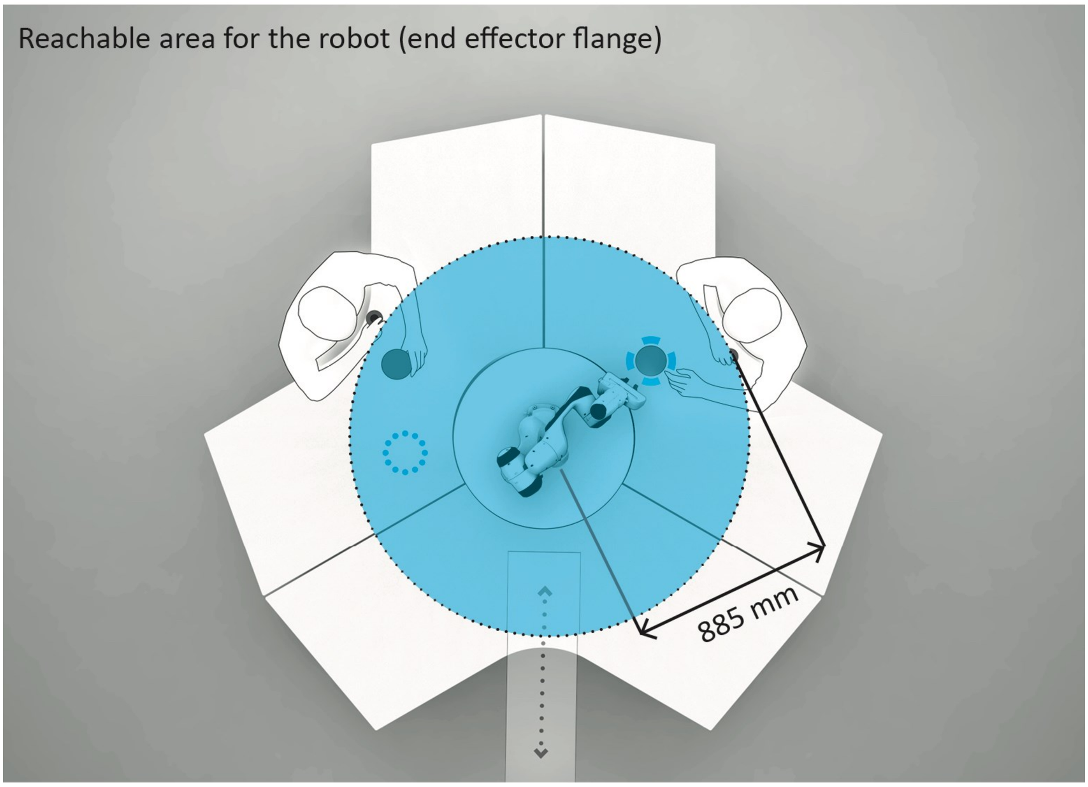


Figure 34 - Concept rendering of the AIWS (2).

The image originally presented here cannot be made freely available via LJMU E-Theses Collection because of copyright.

The image was sourced at Ender, Johanna; Guo, Fang Bin; Larek, Roland. (2018): Design of an intelligent workplace system for human-machine-interaction in the digitized industry. Journal of Applied Mechanical Engineering - V7. 2nd Int. Conf. on Advanced Robotics, Mechatronics and Artificial Intelligence & 3rd Int. Conf. on Design & Production Engineering. Valencia. DOI 10.4172/2168-9873-C2-020

Figure 35 - Concept rendering of the AIWS (3).

Panda is a lightweight robot manufactured by Franka Emika GmbH in Germany. Due to its torque sensors in all seven axes and its rapid collision detection/reaction time it is applicable for HMI. Panda reacts to touch (Franka Emika GmbH 2020a). If it is detecting a collision, it will stop immediately.

Table 11 - Specifics of the robot: Panda (Franka Emika GmbH 2020a).

Specifics of the robot Panda	
Degrees of freedom	7
Payload	3 kg
Maximum reach	855 mm
Guiding force	~ 2 N
Collision detection time	<2 ms
Nominal collision reaction time	<50 ms

Source: Franka Emika GmbH (2020a)

The Panda was installed to this unit and then reallocated to the laboratory (please see Section 5.2). Comparing with classic industrial joint-arm-robots, Panda is equipped with integrated sensors instead of protective cages and also features as low cost and easy/flexible on installation compared with other conventional industrial robots. Therefore, Panda is selected as an ideal product for this experiment for the following reasons:

1. Teach-in programming and manually hand-guided
2. Intuitive and graphical programming GUI
3. Does not require prior programming knowledge
4. Open for programming via Robot Operating System (ROS)
5. Cloud Robotic[25]
6. Sensitivity: torque sensors in all seven axes

This AIWS concept provides an idea of how the design criteria detailed in Section 4.6 can be translated into a workplace design. The following section illustrates the concept of the AIWS regarding User Experience.

[25] The KUKA AG (2016) uses the term Cloud Robotics to describe robots with shared intelligence. Moreover, they are enabled to learn in swarms that means they share learned information via the connected system with other robots and participators of the CPS. Furthermore, they are able to autonomously adapt to various tasks.

The User Experience of the AIWS

1) At the beginning, an operator selects a workplace randomly from the production hall. Based on the flexible office theory such as the Co-working Spaces, Collaboration Platform and/or Desk Sharing, the worktop is available to any operators for free.
2) Then, the operator starts his/her work that employs the worktop as an UI to guide the operator throughout the assembly/maintenance process. The UI directs visual assignments and reminds of break times. Meanwhile, the UI suggesting the status and future moving direction of the robot.
3) The robot helps the operator working on a wide range of tasks, i.e. assisting the operator to make quality decisions through an integrated measurement device that reduces his/her subjective influences. The broad variety and adaptivity of the robotic end-effectors offers the possibility to meet the networked production demand and current tasks. For example, determining the surface quality of workpiece can be implemented by scanning it with a specific effector.
4) The AIWS offers great freedom for operators to interact intuitively with the system:
   - Free division of working time
   - Freedom in choosing the place of work
   - Freedom of selection of the scope of work
   - Adaptation of the work assignment to specific qualifications

5.1.1 Physiological Assistance through the AIWS

When the operator logs into the AIWS through an electronic ID, the workbench will automatically match operator preferred settings, such as the height of worktop, lighting and colour preferences. Moreover, the AIWS will recognise operator's skill set to offer proper tasks. The CPS revises independently to support a specific task, e.g. supplying required tools and workpieces to the workplace with help from the robot.

5.1.2 Cognitive Assistance: Work-by-Light as part of the AIWS

Work-by-light (WbL) is an UI that supports the interaction between operator, robot and network within the AIWS. Derived from the current Pick-by-Light concept that directs the operator to a required stock area, the WbL is guiding him/her to work together with the robot on a specific task. The UI demonstrates future actions of the robot by light signals.

The light signals perform the function of:

- displaying current status of robot, e.g. action, inaction and/or error
- presenting the input/output interface, such as work instructions and on/off/pause buttons
- projecting the direction/position of upcoming movement of the robot on the worktop

Figure 36 illustrates that the WbL minimises information within the working area by displaying light signals on the worktop, so enabling the operator to process instruction rapidly.

Figure 36 - Concept rendering of the AIWS (4).

In order to minimise the operator's cognitive strain and to free extra spaces over the workplace, the worktop was developed as an input/output device. Moreover, an innovative/simplified display technology was developed based on a Light-emitting diode (LED)-matrix that was connected to the high-performance acrylic material and is detailed in Section 5.2 Laboratory Set-up.

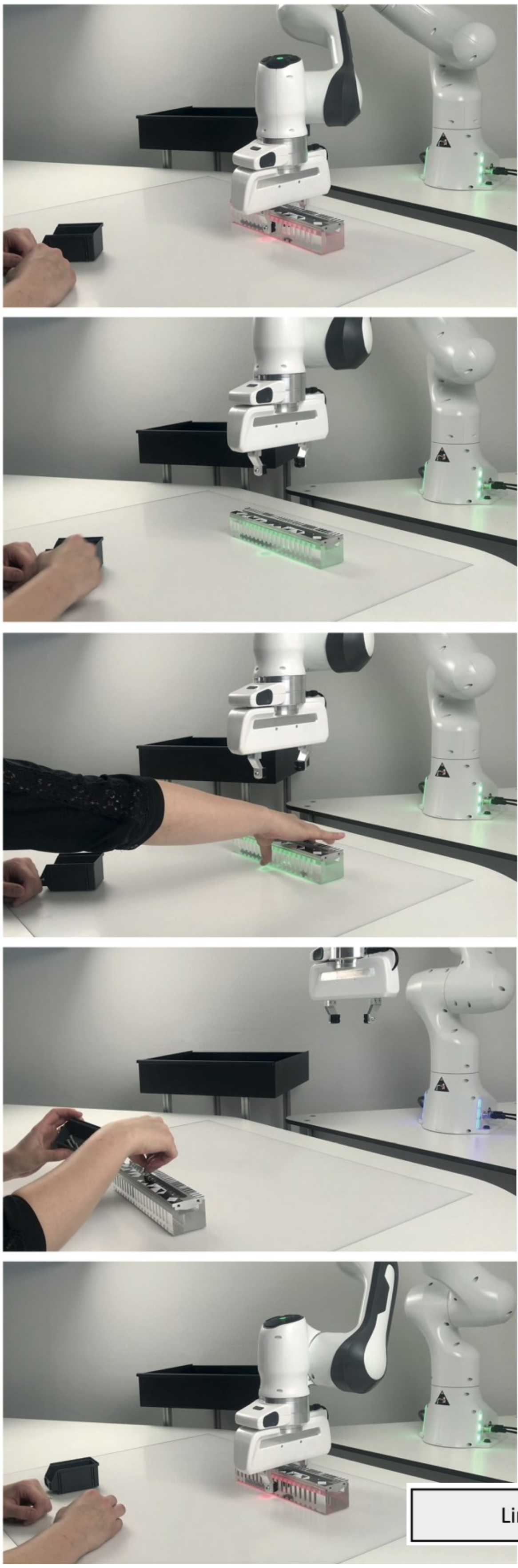
The UI was prototyped to visualise the robotic status/upcoming movements and material/tools inputting/outputting zones. Referring to the HF demand, simplified icons and colours were integrated to support the operator processing information rapidly, please see details below:

Table 12 - Colour-code of the WbL System.

GREEN	Operator can remove/place items from/onto this area.
RED	The robot is operating – do not touch or come close to the marked area.
RED (FLASHING)	The robot will soon move to this area– do not touch or come close to the marked area.

Figure 37 shows sequences of a video that shows the WbL. The upcoming movements of the robot are communicated via the worktop. The color-codes of the WbL as described above have been used to indicate the robot's status and give instructions when the operator can place/remove items.

The system enables communication via gestures as the input of the UI. A camera system identifies the gestures of the operator and transfers the information to the robot control that reacts accordingly. This part of the concept has not been fully integrated within the prototype due to the limited timeframe of this present thesis. However, the necessary devices and the algorithm for detection have already been installed and tested (see 5.2.3 Tracking of Operator and Objects).



Link to Video

Figure 37 - Sequences of a video that shows the WbL.

5.1.3 Organisational Structure of the AIWS

Automated production systems within the digitized factory consist of machines, tool stores, warehouses, manual workstations and the HRC-workplaces. These are constantly networked and sharing their current status with each other. The AWIS extends flexible manufacturing systems by supplying workplaces for hybrid Human-Robot Teams to support manual tasks (Figure 38, Figure 39). Moreover, the AIWS provides a unit for hybrid teams that support operators interacting with the CPS, e.g. undertaking assembly and maintenance tasks within the HRC.

Ender, Johanna; Wagner, Jan Cetric; Kunert, Georg; Larek, Roland; Pawletta, Thorsten; Guo, Fang Bin. (2019): Design of an Assisting Workplace Cell for Human-Robot Collaboration. International Interdisciplinary PhD Workshop (IIPhDW). Wismar. DOI 10.1109/IIPHDW.2019.8755412

Figure 38 - AIWS – Integration of the hybrid production unit for HRC as an advance of the Matrix Production adapted from: KUKA AG (2016). (R-Robot; H-Human).

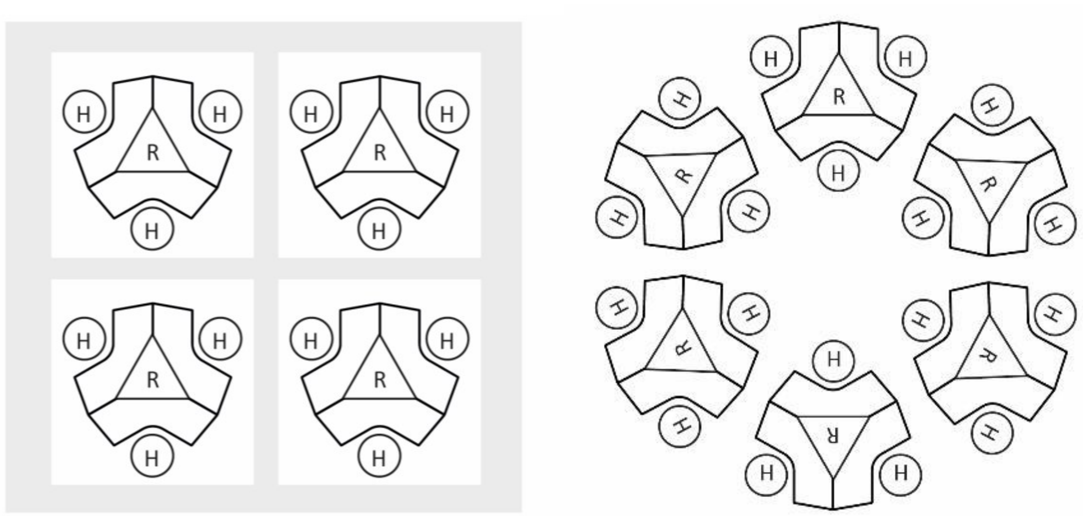


Figure 39 - AIWS - Composition variants of individual units. (R-Robot; H-Human).

The AIWS is designed to be part of Self-Adapting-Production-Planning-Systems (SAPPS). The SAPPS controls dynamically work orders based on the current situation and resource. The Extended Network Plan (ENP) as a subgroup of the SAPPS improves this workflow within the production system (Larek et al. 2019). Furthermore, the ENP demonstrates all necessary steps of product assembly and alternatives of tasks based on the activity on the node method (Wagner et al. 2018).

This system responds to the constantly changing conditions, e.g. machine errors or bottlenecks in the delivery of materials. In the future, the production plant will be able to control both incoming/outgoing materials and available tools in tool stores via an automatic/networked storage system, including conveyor belts, mobile/autonomous vehicles and robots. The required parts/ tools are transferred to a unit consisting of machines or to an AIWS-unit for processing. The AIWS can be used by operators working with one robot.

Furthermore, workplaces at the AIWS can be used for connection/integration of a machine, e.g. two operators and one collaborative robot working with one machine. When the Human-Robot Team is working on the manual tasks, the robot receives parts then delivers them to the targeted operator. The flexible CPS system includes assembly, maintenance, testing and packaging. The whole procedures can now be undertaken on the same workbench.

The concept of the AIWS is designed to satisfy the ergonomic standards listed in 2.3.1 Physiological Limitations - Figure 11 - Relevant groups of standards related to ergonomic workplace design. Thereby the concept must be seen as a basis for further development and specifications within the constructions until the product is ready for mass production.

The concept of the WbL is focussing on the Principles of interaction design of the ISO 9241-110 Ergonomics of human-system interaction – Part 110: Dialogue principles. The following seven principles have been declared as important for the design and evaluation of an interaction system (DIN EN ISO 9241-110):

- Suitability for the user's task
- Self-descriptiveness
- Conformity with user expectations
- Learnability
- Controllability
- Use error robustness
- User engagement

The concept focusses on satisfying the conformity with user expectation and self-descriptiveness by indicating the status/future direction of movements of the joint-arm-robot. Moreover, the concept reduces cognitive load by declutter the workplace. This makes the system suitable for the user's task. The interaction with the system is easy to learn/control as it is focusing on intuitive symbols/color-codes. Further work might focus on the development of the gesture-based input of the AIWS. The user is engaged within the interaction with the robot and the workplace environment and the concept seeks to promote a high level of acceptance and a joyful User Experience/Joy of Use as required in DIN 92419:2020. Investigations of the use error robustness have not been focussed within this present thesis.

The concept of the AIWS has been transferred to a prototype set-up in the Production Technology Laboratory at the Hochschule Wismar, Faculty of Engineering as follows.

5.2 Laboratory Set-up

The ideation/concepts/design of the AIWS/WbL, selection and provision of material, preparation and carrying out the experiment, and evaluation has been done by the author. Mr Daniel Luthardt practically contributed with the technical set up, e.g. the installation of the prototype system and development of the LED-Matrix presented within Section 5.2.2. It was Mr Luthardts task for his master thesis to develop and implement the tracking of operators and tracking of objects (Luthardt 2019).

5.2.1 The Demonstrator Insulation

The key idea of the AIWS is to interconnect the worktop, robot and digital components into a holistic interaction system. Figure 40 visualises these components of the AIWS. The operator's behaviour is monitored by a camera to ensure all components are networked with the CPS. The data recorded includes operator's position, moving trajectory, workpieces and spare spaces of worktop, and will be transferred to the central processing system (a computer), then provided to the robot controller/micro controller that is controlling the UI.

Ender, Johanna; Wagner, Jan Cetric; Kunert, Georg; Larek, Roland; Pawletta, Thorsten; Guo, Fang Bin. (2019): Design of an Assisting Workplace Cell for Human-Robot Collaboration. International Interdisciplinary PhD Workshop (IIPhDW). Wismar. DOI 10.1109/IIPHDW.2019.8755412

Figure 40 - Structure and communication of the single actuators of the AIWS.

Finally, the operator can communicate with the system via body position/gesture tracked by the camera. In addition, the system can display information via modifying the workplace/environment[26], e.g. robotic movements and the WbL. Based on this concept, the experimental workplace for understanding user acceptance was constructed at the laboratory as shown in Figure 41.

[26] Further, connections to elements characterising workplace environments can be integrated. Not yet implemented but imaginable would be the connection of ambient light and biodynamic light to adjust to specific requirements of the operator.

Figure 41 - Installation of the AIWS workplace at the laboratory Hochschule Wismar.

5.2.2 The LED-Matrix Technology

Supplied by the LOTTE Advanced Material Company, the author developed a display technology based on an LED-dot-matrix connected with the high-performance acrylic material *'Staron'*[27]. The LEDs are illuminating under the translucent material. The LED-Matrix is

[27] The Manufacturer supports the study by contribution of large-scale material samples.

controlled by a microcontroller, and displaying red, green and blue (RGB) colour images from the computer. The microcontroller extracts the individual pixel information from the image and generates/controls individual LED. A student project assisted in assembling, programming and testing all electronic parts.

A prototype was developed within three iterative stages:

(1) Development of a 100 x 100 mm matrix (see Figure 42).

(2) Development of a 600 x 700 mm matrix (see Figure 43).

(3) Integration of (2) in the workbench surface (see Figure 44).

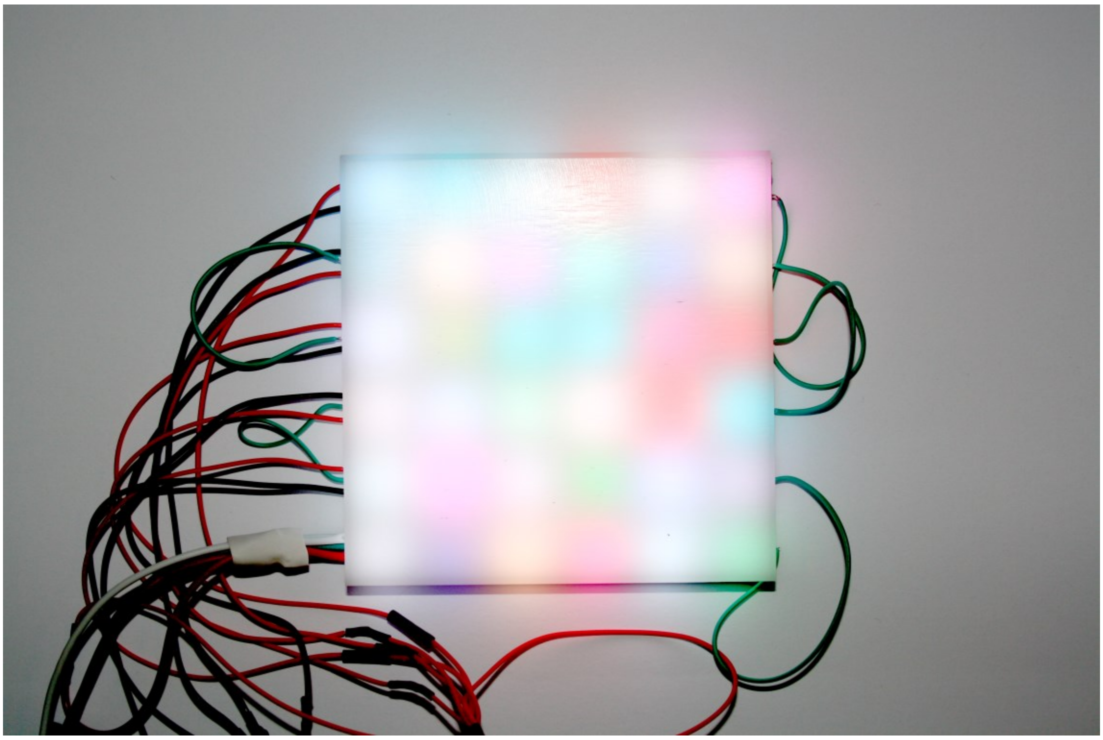


Figure 42 - (1) Development dot-matrix.

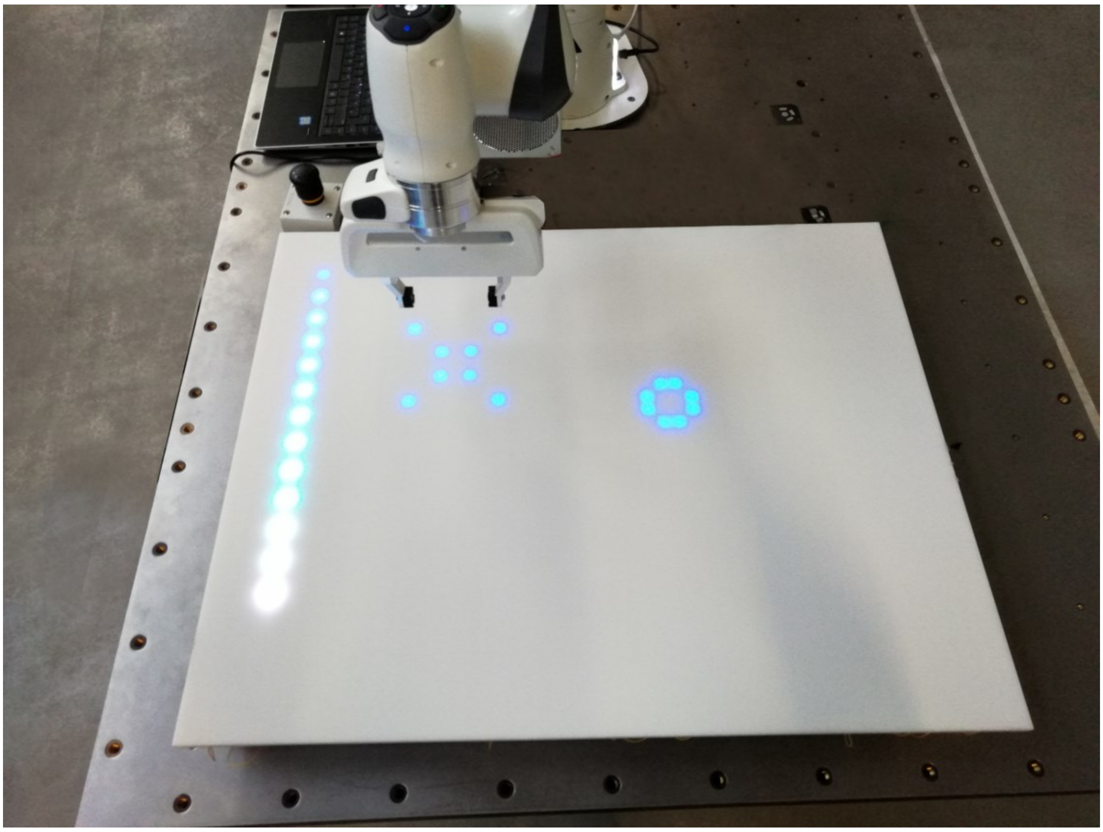


Figure 43 - (2) Development dot-matrix.

Figure 44 - (3) Integration of the dot-matrix within the AIWS prototype.

5.2.3 Tracking of Operator and Objects

The UI works as a communication channel between the operator and system, also visualises/detects operator's gestures/positions and objects' locality via the affiliated camera. Integrating objects and operator's trajectory is a sub-project on which the author worked collaboratively with a master's student (Luthardt 2019), and the details are introduced below.

- **Detecting objects**

The detection of objects was implemented by the image recognition algorithms from the library's Open Computer Vision, where, objects' images such as tools/workpieces are stored in an image database, that can be used for image recognition later. For this purpose, the noticeable points (so-called key points) of an image are detected/compared with the images in the database. When setting up the object's detection within the demonstrator, the detector Oriented fast Rotated Brief (ORB) and AKAZE was implemented. Figure 45 illustrates a remote-control unit that featured with a high-contrast appearance resulting from the strong contrast between bright body and dark buttons.

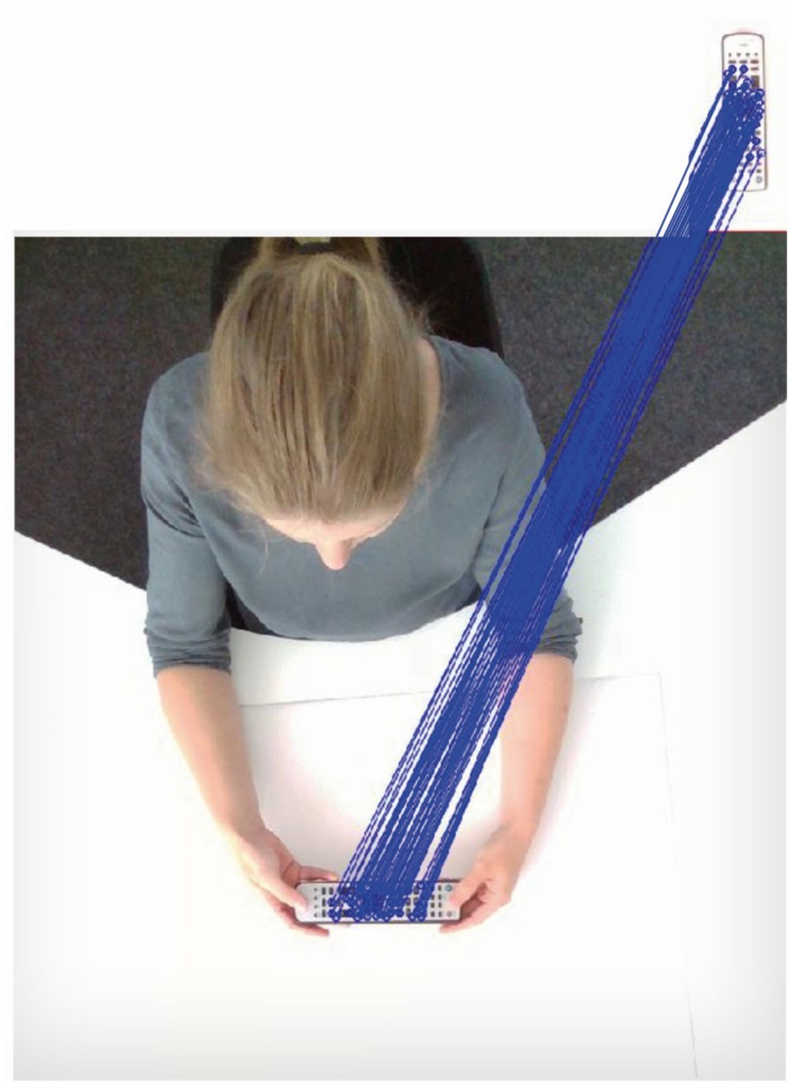


Figure 45 - Detection of objects. Graphical representation of the connections of matching keypoints detected by the algorithm ORB.

The recognised/matched key points are visualised by blue circles and connected with blue lines. Depth measurement will detect objects which are not stored in the database such as operator's personal belongings. Then, the stereoscopic camera will check the worktop to see if objects can be detected, if yes, then the position will be allocated.

- **Detecting the operator**

The open-source algorithm: *'Open Pose'* can detect operator's position and dimensions. Figure 46 illustrates how the Open Pose detects the skeletal structure and visualises the body dimensions by colouring different lines.

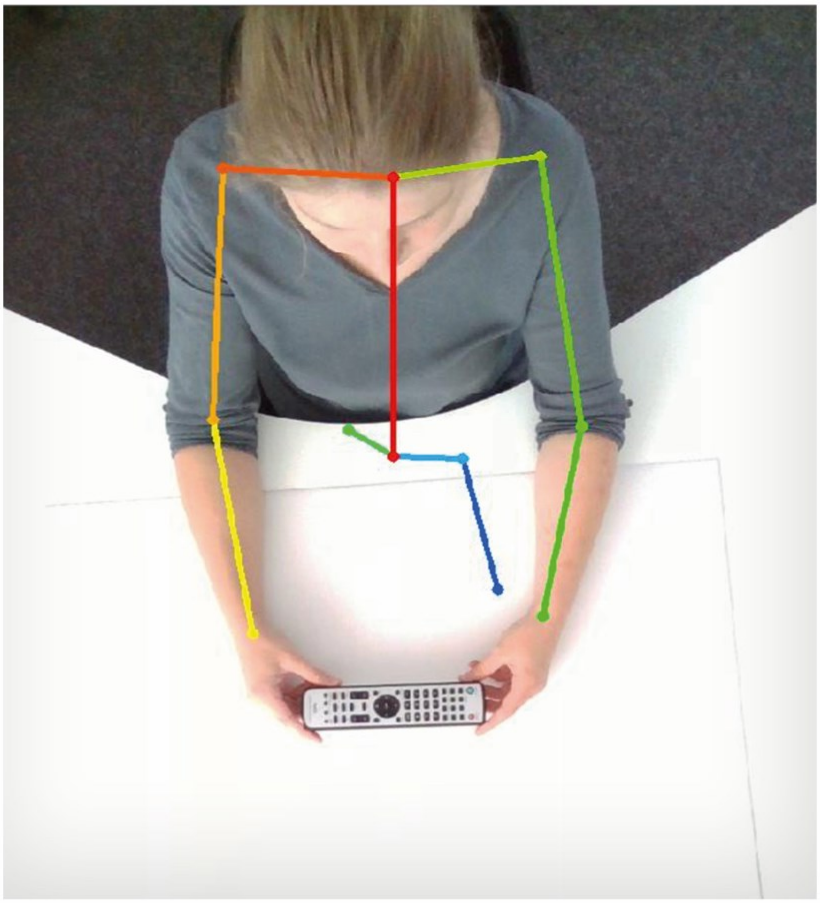


Figure 46 - Detection of the operator. Graphical representation of the skeletal structure of the operator recognized by the Open Pose System.

Figure 47 illustrates how to detect the operator's skeletal structure (the top image), so as to define the forbidden zone of the robot (the bottom image). The red area is adjustable, it can be enlarged/shrunk according to security requirements. The raster can be refined. The bottom image demonstrates an example of simplified raster, transferring the dimensions/positions of object to the robot control program. The area marked green (the bottom image) is indicating objects which are placed randomly on the worktop that the robot is to grab.

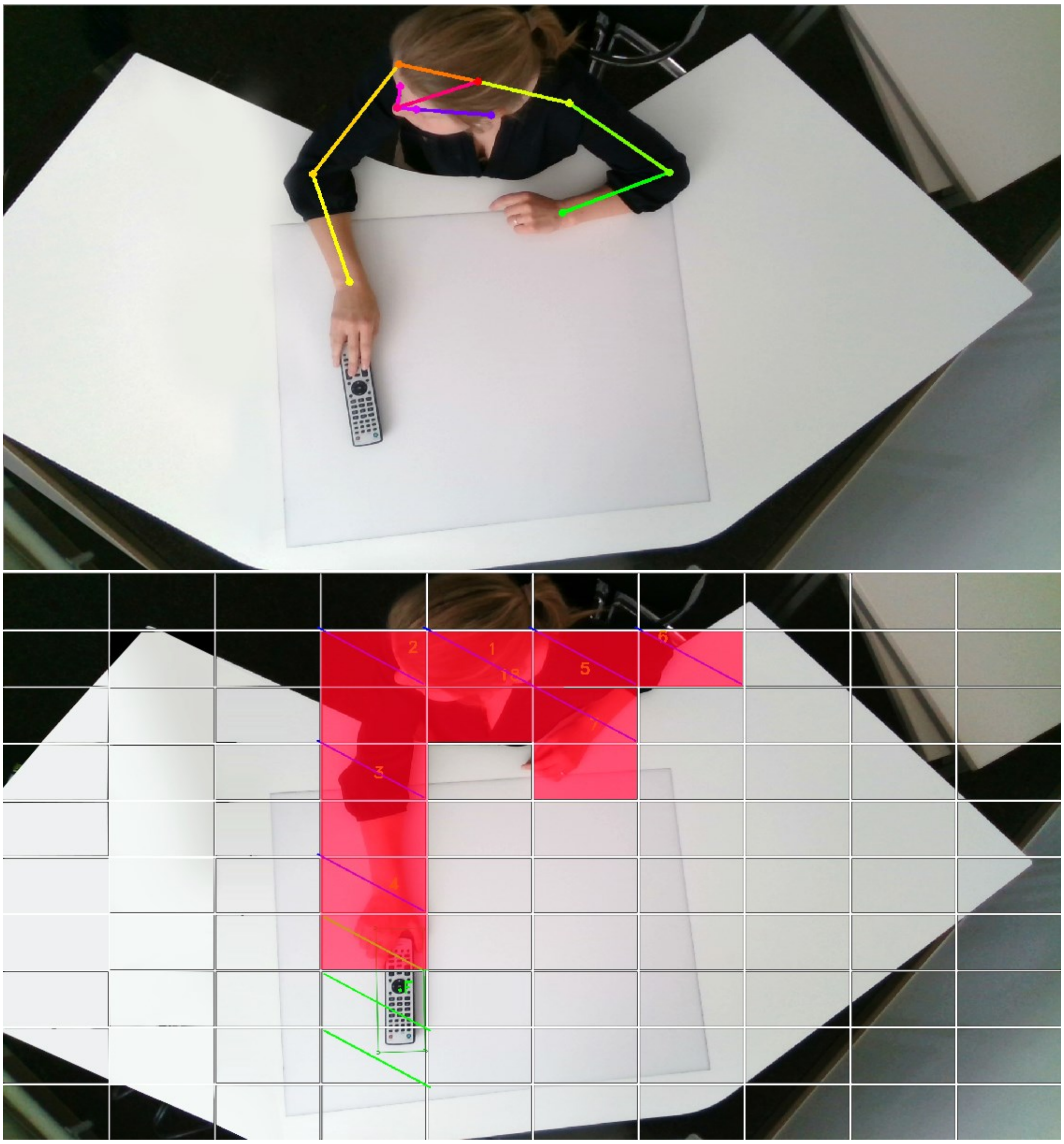


Figure 47 - Above: Operator detection: Visualisation of the skeletal structure. Below: Combination of objects and operator detection. Red zones indicate restricted areas for the robot.

Detecting objects and the operator is crucial for developing the AIWS, as it will ensure the whole system adapting to the specific/inconstant behaviour and performance variability of each operator. Therefore, the robot must proactively adapt to the constant changing mode of the operator.

Human behaviour cannot be fully predicted; therefore, the rigid control programme will not be able to fulfil this task. In this case, the AI technology will be employed to develop a high-flexibility and self-learning robot control programme. Seeking possibility of connecting the ML to the programme of controlling demonstrator is part of the concept development of the AIWS. Therefore, developing an intelligent robot control system for the demonstrator is scheduled as further work and will be undertaken by the CEA in Hochschule Wismar, University of Applied Sciences: Technology, Business and Design in the future. Please see the schedule below.

5.2.4 Self-adapting Robot Control

The operator inputs information through the operator's gestures tracked by the camera. The control-computer inspects the entire workplace/environment through the camera and decides with assistance of learned behaviour. The detected information will be transmitted to the control-computer and further to an AI component of the mainframe. The mainframe processes this data through post-optimization/reinforcement learning (Kunert and Pawletta 2018) and adjusting the behavioural strategy. After that, the control-computer will receive the new behavioural strategy and generate the robot control programme from the learnt behavioural strategy. The self-learning robot control programme will be able to interact with the operator independently through a model-based learning pattern. The programme is also expected to respond adequately to the unknown circumstances.

The learning process consists of two steps: the real-world process will be simulated with a model and learned (i) offline with the post-optimizing/reinforcement learning; then the ML needs to improve (ii) online during the entire operating time. The following system elements are derived from the concept and will be developed/implemented by the CEA as an autonomously learning robot control programme:

- Secure movements will not be hindering/distracting the operator
- A robot control programme will proactively respond to the operator's individual behaviour

When learning offline, the reinforcement learning algorithm switches between the exploration (acting randomly and finding new states) and the exploitation (choosing the best-known actions to reach as fast as possible the given target). Switching between these two modes, the algorithm learns alternative behavioural strategies for problem-solving.

When learning offline, the control-programme will continuously examine the safety of the operator within the workplace/environment. After the offline learning, the algorithm must proactively learn online in the real environment. Even if a path of the robot is blocked by an operator or an obstacle, the algorithm will select an alternative route for the robot moving to the targeted position without disturbing the operator.

Since the development of the self-learning robot control has not been finished, the proactive reacting robot control is simulated within the experiment of this research by applying the method of *Technique of the Wizard of OZ'* as mentioned in Section 3.2.3.4.

For an indication of an individual's cognitive strain, an evaluation method has been developed. Finally, an objective, task-related classifier for cognitive stress recognition using Electroencephalography (EEG) is presented as a result of this research and detailed within the following section.

5.3 Development of an Objective Workload Detection Method

The secondary research/ideation/approach of the Objective Workload Detection Method has been done by the author. The author has chosen the technology, selected the device, organised, prepared and carrying out the experiment and evaluated the recordings. The evaluation method was developed through cross-disciplinary cooperation with the CEA of Hochschule Wismar at the University of Applied Sciences: Technology, Business and Design. The executive programming of the algorithm was implemented by Mr Georg Kunert, researcher of the CEA, who further optimised the algorithm in collaboration with the author.

An experiment was conducted during the methodology development. The method employs the EEG for data collection of event-related neuronal activity. Based on the EEG-Data, a supervised ML algorithm was trained for pattern recognition of brain wave frequency to understand objectively the stress level of the subject. In addition, this data classifier method has successfully been validated by comparing the outputs of the EEG and the scores of the NASA Task Load Index (NASA TLX) - an indicator for perceiving workload subjectively. Consequently, this method demonstrates clearly the effectiveness of future HCD research by assessing user's neuronal activity.

5.3.1 Review of Current Measurement Methods

Currently, existing approaches to the assessment of mental state can be divided into the following categories:

- **Subjective measurements**

The subjective perceived workload can be measured by analysing the self-report of the subject's mental status/emotion after completing a task. A broad range of techniques/methods have been developed within the scientific discipline of the HFE as follows:

1. SSWAT: Simplified subjective workload analysis technique (Luximon and Goonetilleke 2001)
2. WP: Workload Profile (Tsang and Velazquez 1996).
3. NASA TLX: National Aeronautics and Space Administration Task Load Index (Hart and Staveland 1988)

The NASA has developed a reliable assessment technique to measure the subjective mental workload of tasks (Hart and Staveland 1988).

The software application NASA TLX was used for the collection of:

1) factor weights
2) ratings of the tasks

The participants have been given a description of following factors:

- Mental Demand
- Physical Demand
- Temporal Demand
- Performance
- Effort
- Frustration

Afterwards, the participants have been asked to indicate how important those factors are towards their subjectively perceived workload. Therefore, the participants have been asked to compare the factors pairwise to choose the most relevant factor. This procedure delivers an individual weighted score of each factor that is further processed within the rating score.

The NASA TLX then results in a weighted rating score which ranges from 0 to 100. The score displays the subjective workload of the subject concerning the specific task. A score 0 indicates that the participant did perceive minimum subjective mental workload; 100 means that the participant did perceive the maximum subjective mental workload. The method presented through this research work uses the results of the NASA TLX as the subjective measurement method, to validate the analysis of the objective measurement of participants' stress level.

- **Objective measurements**

Apart from measuring heart rate and heart rate variability, there are various physiological signals that are associated with a human's stress level such as skin/body temperature, cortisol level, blood pressure, eye blink rate and pupil dilation. After comparing commercial physiological and emotional monitoring devices for stress detection, Taj-Eldin et al. (2018) employed the EEG to analyse the neuronal activity by measuring the brain's electric voltage due to its non-invasive feature. For the purpose of observing arousal of the central nervous system, the voltage of electrical brain activity is recorded via electrodes at the head surface. The EEG can plot waveforms to show the electrical activity of the brain, such as event-related potential (ERP), averages, fluctuations, peaks and pattern. Regardless of which EEG device is used, the signals of each electrode must be processed after recording.

Since 1920, research has dealt with the analysis and classification of EEG data to detect mental states (Biasiucci et al. 2019). Different approaches are using computational methods for analysis of the EEG dataset: Research focuses on the division of the signals into frequency bands, such as Delta (0.5-4 Hz), Theta (4-7.5 Hz), Alpha (7.5-13 Hz), Beta (13-38 Hz) and Gamma (38-higher Hz) (Jebelli et al. 2018), and correlation of those frequency bands to mental states. By applying such frequency band division, the EEG-based Workload Index (EWI) was developed for measuring an operator's mental workload (Choi et al. 2018).

Furthermore, research is focused on peaks in the alpha power spectrum or cross-correlation between averages of all electrodes for the alpha ranges (Schaaff and Schulz 2009; Legewie et al. 1969). By computation of power spectral densities, Scholz (2014) defined so-called attention profiles for classification of different attention types. Unfortunately, these systems suffer from limitation: EEG power values differ from individual to individual subjects and show diverse patterns of psychophysical reactions (Goschke 2013/14).

To overcome this limitation, greater attention is currently paid to the usage of supervised ML for EEG data analysation: Research applies different algorithms, e.g. Support Vector Machine (SVM), Naive Bayes, Bayes Net, k-Nearest-Neighbour, to correlate patterns in spectral frequency bands to mental states (Hou et al. 2015b; Bird et al. 2018). Unfortunately, the division into EEG frequency ranges lacks standardisation, but also the literature shows a broad variation and sometimes even ambivalent allocation towards mental states.

In recent years, few researchers have addressed a combination of ML algorithms to analyse the objective measurements and parallel concerning subjective feedback methods: In Arsalan et al. (2019), the authors utilised SVM, Naive Bayes and Multilayer Perceptron for EEG data analysis and compared the results to the perceived stress scale of the subjects. Several other studies, for example, Fan et al. (2018), used a combination of SVM and self-ratings for classification of mental states. Furthermore, the CogniMeter was developed by utilising theta frequency in correlation to the result of the subjective measurement (Hou et al. 2015a). Likewise, comparing EEG-Data with scores of the NASA TLX (Chen et al. 2017; Liu et al. 2017) led to an indicator of individual mental states of the subjects.

Given the discussions above, the research methods employed in this PhD project were as follows:

I. classifies individually referenced brain activity using ML and

II. validates the outputs from I. with subjective perceived load ratings utilizing the NASA TLX.

This method is in line with a variation of Liu et al. (2017), however, instead of applying a Support Vector Machine as the ML algorithm in their research, the author employs an artificial Neuronal Network (NN) which is trained for classifying the EEG data as detailed below.

5.3.2 Data Recording and Data Classification for Objective Workload Detection

The method conducted in this PhD research employed the Supervised ML algorithm to train the classifier on individual EEG datasets of the subject. In order to assure the algorithm to detect the stress level of unknown datasets, the supervised ML has been recognised as a standard training method in the field of AI, to be used to train the NN to apply a label to a given input dataset (The MathWorks 2019).

A NN is able to detect mental condition: (1) relaxation and (2) stress. Therefore, pre-classified/labelled data of the subjects are collected as Reference Recordings and are processed for Model Building.

Figure 48 illustrates the roadmap of data collection. The collection including the EEG data recordings. The NASA TLX is collected for validating the EEG data analysis outputs. In order to identify an individual's stress level while undertaking any task (such as Task C), the method requires the collection of reference data. Therefore, two tasks (A and B) are required. Task A requires the subject to relax and open their eyes, e.g. watching a calming picture for a given duration. Task B proposes a task to activate/challenge the subject, e.g. playing a puzzle under time pressure for the same duration as task A. The EEG signals are recorded when the subject is working on both task A and B. In order to collect the learning data and validating the classifier, each task must be undertaken twice so that four references for classification can be recorded (Task A: Ref. I; Ref. II; Task B: Ref. III; Ref. IV).

Before working the first task, participants are required to rank the NASA TLX factors for individual assessment of workload. After each task, subjects need to rate the NASA TLX. Based on the data recorded, the classifier was trained as follows.

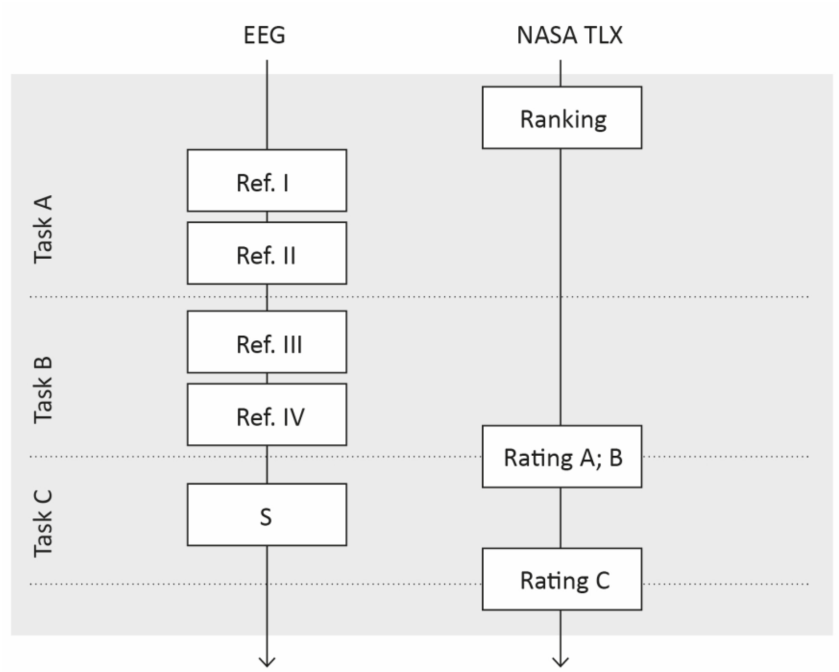


Figure 48 - Roadmap of data collection for mental state detection.

An NN has been selected as the Supervised ML algorithm for Model Building. The NN model was trained with the 'MATLAB – Deep Learning Toolbox 2019b' utilizing 1,200 input neurons and four hidden layers. The first hidden layer has 3,000 neurons, the second layer has 1,600 neurons, the third layer has 1,600 neurons and the fourth layer has 1,000 neurons. The output layer has two neurons: one represents high cognitive workload and the other represents low cognitive workload. The output of the classifier indicates a value to each neuron. The height of the value demonstrates the confidence of the NN decision. Figure 49 illustrates the process of the training, validating and classifying by the usage of a trained model.

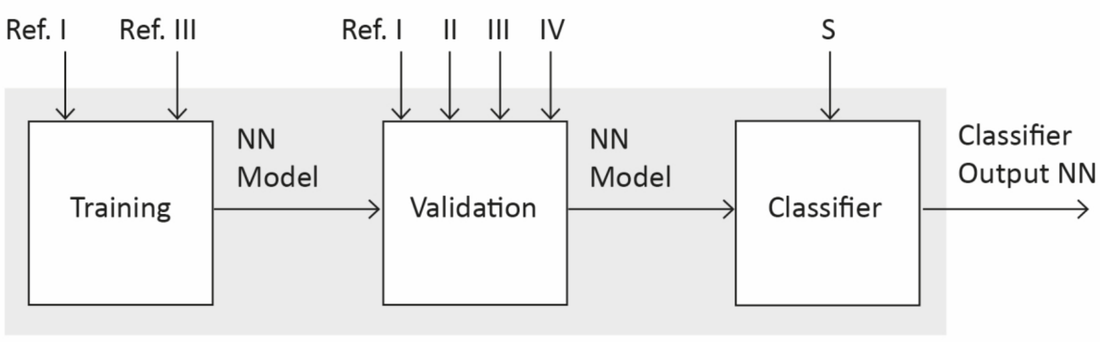


Figure 49 - Classification of measurement data set using trained models.

The NN model is trained using the two classified reference datasets, Ref. I and Ref. III. However, Ref. I represents a dataset of a more likely relaxed subject, while Ref. III represents a more likely stressed subject. Then, the model is validated by classifying the learning data, Ref. I and Ref. III and classifying the until now unknown data, Ref. II and Ref. IV. Since the classifier is well-trained, it will identify confidently all classifier states of all four datasets of each subject. Finally, the classifier is now able to apply the pre-trained model to classify unknown datasets, e.g. scenario (S). The algorithm will now be able to identify the individual's workload level related to any future task (Task C) by analysis of the individual's recorded EEG data.

5.4 The Assessment of the AIWS concept

This section discusses how the AIWS supports manufacturing tasks in a scenario of digitised industry, and to evaluate how the AIWS can increase the acceptance of Human-Robot Teams by improving the operator's well-being and reducing their strain level. It is expected that the AIWS will reduce the operator's strain massively. It has been validated within the controlled experiment over the demonstrator, in which the perceived workload of the HRC was determined.

This research method has been reviewed/accepted by the Liverpool John Moores University Research Ethics Committee (Reference number: 19/EEE/001).

5.4.1 The Aim of the Assessment

In order to assess the result of design-decisions, an HF assessment method re cognitive stress recognition through biometrical data tracking was developed/validated within this study. The method detecting/comparing participant's stress level while they are working collaboratively with a joint-arm-robot to undertake assembly tasks is detailed as follows:

S. I	Participant's stress level working with the assisting light guidance concept WbL of the AIWS.
S. II	Participant's stress level working without the assisting light guidance concept WbL of the AIWS.

The method uses the ML algorithm for recognising event-related brainwave frequencies that are recorded by a mobile EEG device.

5.4.2 The Participants and Location

10 students (age ≥ 18 years old) from the Hochschule Wismar, University of Applied Sciences: Technology, Business and Design, have participated in this study. Participants were recruited through an advert poster published over the university campus. All volunteers have registered and consented for the experiment. Data were stored anonymously, however, data sets and

personal information are not identifiable for personal data protection purposes. The exclusion criteria have been declared as follows:

- Anxiety conditions and/or receiving medication for anxiety conditions
- Head injury conditions
- Coffee consumed less than 2 hours before the start of the experiment
- Wearing glasses during the experiment.

The assessment took place at the Production Technology Laboratory in the Faculty of Engineering, at the Hochschule Wismar, University of applied sciences: Technology, Business and Design. The registered address is Philipp-Müller-Straße 14, 23966 Wismar in Germany.

5.4.3 Preparation for the Assessment

As a part of the concept of the AIWS, the demonstrator was placed in the laboratory for assessing the HMI (Figure 50). The demonstrator consists of a lightweight robot-Panda, produced by the company Franka Emika GmbH and a black box to simulate the real-world scenario. The box imitates the paint shop, tool store, warehouse and oven to demonstrate the scenario of pigmentation process.

Figure 50 - Laboratory set-up of the AIWS for evaluation of the demonstrator.

Aero-Coating GmbH supplied workpieces that fit the experiment to demonstrate the real-world process (see Figure 51).

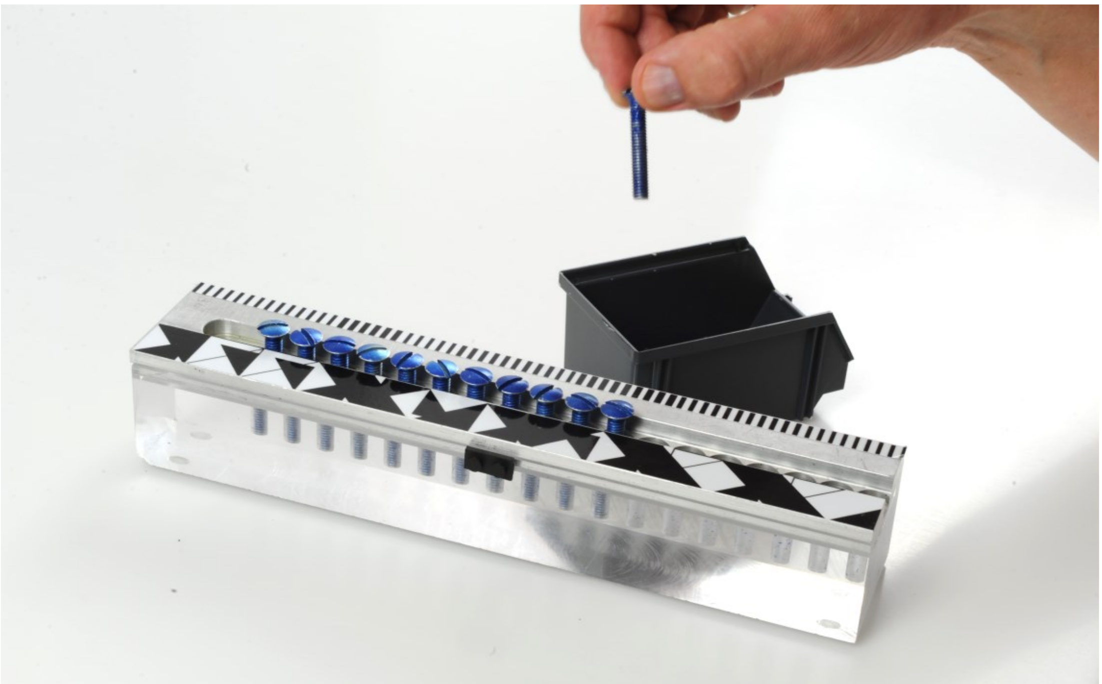


Figure 51 - Experimental set-up: Masking rail with marker, screws and container.

The masking rails were cut in half and supported by a translucent substructure for easy use. Furthermore, the recognitive markers were placed to enable the masking rail tracking through the AIWS. The recognition was not activated while running the experiment. The recognition and the affiliated robot control were simulated in the experiment. The self-adapting robot control - has not been fully developed/integrated. This did not impact the main research questions, as this study examines the cognitive relief due to applying the WbL. The subjects were not aware that the object recognition was not activated. Table 13 describes the order of the tasks which have been simulated within the experiment.

Table 13 - Order of tasks of the experiment conducted.

Stocking of masking rail	
a)	The robot delivers container with untreated screws from the warehouse onto the operator’s table.
b)	The subject takes the container.
c)	The robot delivers a masking rail from the warehouse onto the operator’s table.
d)	The subject takes the masking rail.
e)	The subject stocks the masking rail with screws.
f)	The subject places the masking rail on the output area.

g)	The robot removes masking rail from the output area and places the component in the paint shop.

Removing components from masking rail

a)	The robot delivers masking rail with treated screws from paint shop onto the operator's table.
b)	The subject takes the masking rail.
c)	The subject removes screws from the masking rail and fills screws into the container.
e)	The subject places the empty masking rail and the container on the output areas.
f)	The robot removes masking rail and container from the output areas and places the components in the warehouse.

Figure 52 illustrates the layout of the experimental area and the positions of all parties.

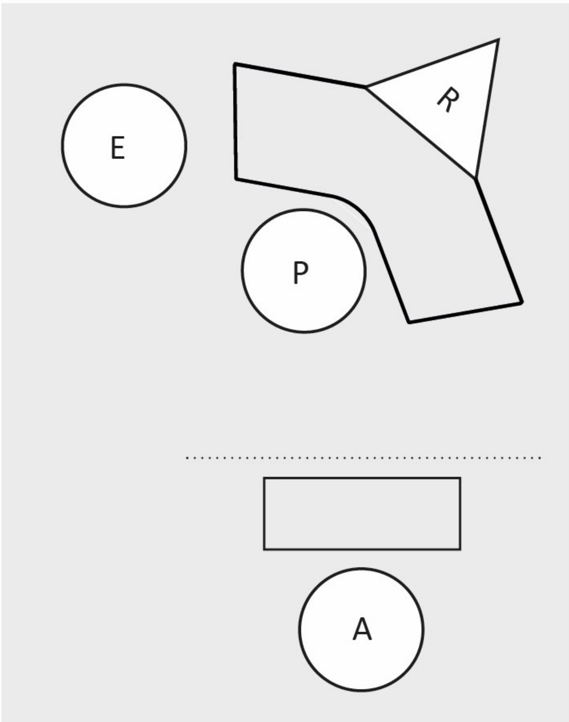


Figure 52 - Description of the experimental room. E- Experimenter; P-Participant; R-Robot; A-Assistant

Where the robot (R) was fixed on the worktop, and participant (P) was positioned in front of the robot. The experimenter (E) was placed close to the system for security purposes, when the participant interacts with the robot. (P) was given a presentation of the AIWS concept. (P) was not aware that some components are not activated/involved. An assistant (A) was placed nearby the AIWS, but not in the field of vision of (P). Following the *'Technique of the Wizard of OZ'* (see Section 3.2.3.4) (A) was simulating following parts of the system while interacting with (P). The object detection would have been connected to the LED Matrix on the worktop. The WbL would generate a light signal to the positions of in/output areas of material, tools and components. This was stimulated by (A). Furthermore, the WbL system indicates the upcoming movements of the robot and its status. To test the cognitive relief due to the WbL System, this was simulated by (A) within scenario S. I. The following section describes the process of the experiment.

5.4.4 The Assessment Process

All participants have gone through the following process during the experiment:

1. *Informed consent:* The participant was required to read the information and sign the consent form after an introduction of the project presented by the experimenter, which includes the aim/objectives of the experiment and the AIWS concept, so as to understand/agree the requirements of the experiment.
2. *The EEG placement:* Muse 2 is a lightweight, head-mounted EEG-device. The participant was required to wear it on their head to measure the neuronal activation of the brain during the experiment.
3. *NASA TLX feedback form - ranking:* The subjects were required to rank the factors of the NASA TLX by using the NASA TLX App.
4. *Referencing:* The neuronal activity of the subjects was recorded. Therefore, the EEG data were recorded when undertaking the reference tasks.
5. *NASA TLX feedback form - rating:* After finishing the reference tasks, the subjects completed the feedback form to show their subjective perceived workload regarding the tasks individually.
6. *Demonstrator trails*: The participants were required to undertake simple assembly tasks that working collaboratively with the lightweight robot. The participants were organised randomly in two groups. Group A started with the scenario S. II, group B started with the scenario S. I. The groups contained equal proportions of male and female participants.
7. *NASA TLX feedback form - rating:* After running the demonstrator trails, the subjects have been asked to complete the feedback form to indicate their subjective perceived workload at each scenario.

8. *Debrief:* The experimenter and participant reviewed the experiment after completed the whole process.

5.4.5 Data Recording

A) EEG Data

Within this experiment, EEG signals and feedback forms of 10 subjects have been recorded. For each subject, four EEG recordings (Ref. I; Ref. II; Ref. III; Ref. IV) have been used for model training and validation and two EEG recordings (S. I and S. II) for model application:

- Task A: (Ref. I; Ref. II)
- Task B: (Ref. III; Ref. IV)
- Task C: (S. I; S. II)

Task A: Recording of Ref. I and Ref. II, the subjects were required to relax, and watching a picture of a sunset for 3 minutes.

Task B: For the recording of Ref. III and Ref. IV, subjects were asked to solve mental arithmetic which had been presented to a monitor with a duration of three minutes and a clock rate of two seconds. They have been asked to say the answer aloud. If the answer was incorrect, acoustic feedback was given.

Task C: Afterwards, the subjects were asked to solve task C as described in Table 13 under differing scenarios.

S. I Subject working with the assisting light guidance concept WbL of the AIWS.

S. II Subject working without the assisting light guidance concept WbL of the AIWS.

The expectations, acceptance and natural reactions of subjects were determined in the test environment using a physical prototype and workpieces related to the practical case given by the cooperating practice partners from the aerospace supplier, Aero-Coating GmbH. In S. I the AIWS provided light signals to indicate the future movement-directions of the robot, input and output areas on the table surface, so the participants were able to put onto/ or remove the container and holder. Additionally, the AIWS indicated in S. I, when the robot was ready with its handling and indicated when the operator was allowed to take delivered parts from the input area. Each scenario solving the assembly tasks has taken approximately three minutes.

Also implemented within S. I was the following simulation. A white light occurred on the surface of the table, motivating the subject to touch it by pulsating. When touched, the set-up simulated that the AIWS was activated. White lights started to travel above the surface of the table and the robot started to move slightly. This simulation of the system's start was integrated to welcome the participant in order to let the subject familiarize themselves with the WbL system as well as with the movements of the robot. This sequence of the neuronal activity was not recorded for data analysis.

Figure 53 shows Muse 2 manufactured by InteraXon Inc. Muse 2 is an EEG device which is widely used by neuroscience researchers (Armanfard et al. 2016). In support of this, research by the Neuroeconomics Laboratory, Centre for Biomedical Research, University of Victoria, Canada, justifies the high quality of the portable and low-cost EEG for collection of reliable ERP components in the field and clinical environments, even in comparison to conventional laboratory systems (Krigolson et al. 2017).

Figure 53 - Portable EEG device - Muse 2.

The device was placed and adjusted to the participant’s forehead to measure the neuronal activation while running the experiment. The correct position can be seen in Figure 54.

Figure 54 - Positioning of the device on the participant´s forehead.

The Muse 2 device has four electrodes that measure independent voltages of brainwave activity (MUSE Monitor):

- AF7/ FP1
- AF8/ FP 2
- TP9
- TP10

Depending on the position height at the forehead, the area of the electrode measures the area FP1/FP2 instead of the area around AF7/AF8. The subjects should not wear glasses, as this may interfere with the measurement because the positioning of the sensors could be disturbed by the frame.

Figure 55 illustrates the position of the electrodes according to the international 10-20 system (Klem et al. 1999). Highlighted are the sensors AF7, AF8, TP9 and TP10 of the Muse 2 Headband.

The image originally presented here cannot be made freely available via LJMU E-Theses Collection because of copyright.

Figure 55 - Electrode positions of EEG - international 10 –20 system. According to: Klem et al. (1999).

Parallel to the recording of EEG data, the subjects were asked to rate their individually perceived workload experience by completing the NASA TLX form as follows.

B) NASA TLX

Figure 56 illustrates the interface of the rating process example for one factor given by the application.

The image originally presented here cannot be made freely available via LJMU E-Theses Collection because of copyright.

Figure 56 - Interface-segment of NASA TLX rating process – factor mental demand (Hart and Staveland 1988).

An example plot from the application concerning the factor weight and rating is demonstrated in Figure 57. The index indicates the subjectively perceived workload of one subject while running the scenario.

Figure 57 - Exemplary plot of NASA TLX – Weighted Rating (Hart and Staveland 1988).

The scale ranges from 0 to 100, which means that a score around 90 (as seen in Figure 57) indicates a high level of load. This weighted rating was conducted by every subject concerning Task A, B and C (S. I; S. II) separately and was used to validate the EEG data analysis of the method developed within this study.

5.4.6 Data Processing and Analysis

1) Data processing

The following applications were used for data collection and evaluation:

- Muse Monitor App
- MATLAB
- NASA TLX App

The raw EEG signals of each electrode are recorded by the Muse 2 device. The voltage sensors record the signal with a step size of 256 Hz. Each Reference Recording interval was set to three minutes. The duration of S. I and S. II is determined by the time it takes each subject to complete the task. This differs individually in its length.

Moreover, the experimental interval of one single subject, exclusive S. I and S. II, delivers a minimum of 46,080 data points for each sensor. The exemplary measurements of all sensors from one recording are shown in Figure 58.

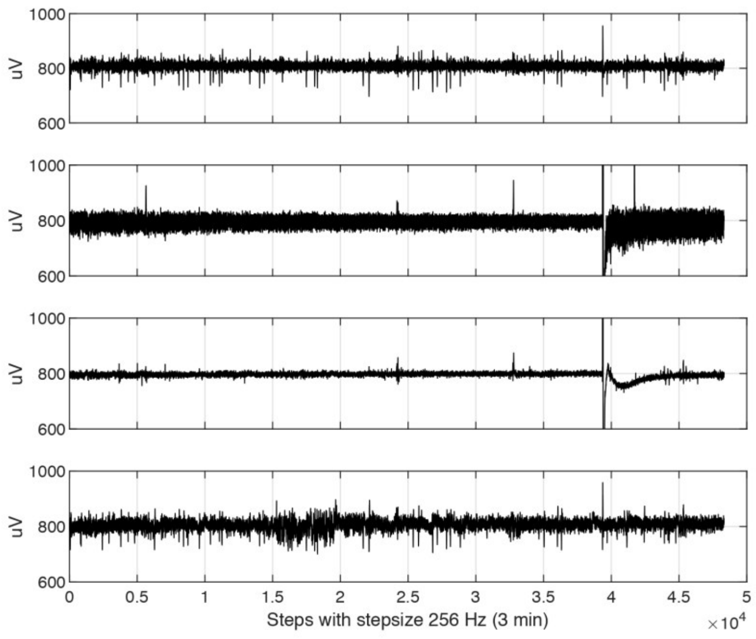


Figure 58 - Exemplary measurement data of all four sensors.

Further computing of the data is performed by using MATLAB software as follows.

2) Sliding window

Each signal of each sensor is divided by the sliding window procedure. The signal is sampled through a width of 5 s and a shifting distance of 1 s. The last four windows will be deleted because they do not have the length of the other windows. This method results in 176 windows; because of the recording step size of 256 Hz, each will deliver 1,280 data points. The model classifies every window of a dataset. Moreover, the output of the whole classifier is the average of all classifications over all windows of one measurement recorded.

3) Learning Data

By applying the Fast Fourier Transformation (FFT), each window will be transformed from the time domain to the frequency domain. This delivers a vector that is further processed by limiting the vector to 300 elements. This vector includes frequencies from 0.2 Hz to 60 Hz with a step size of 0.2 Hz.

Afterwards, the data of the four sensors of each window are combined in a row vector. Then, all windows of a measurement recorded are vertically connected to a matrix. In total, each Reference Recording delivers a minimum of 176 x 1200 matrix.

One main issue in the training of the NN is the occurrence of the phenomenon, so-called overfitting. The term overfitting relates to the fact that during the training, the network tends to correspond too closely to the original dataset, e.g. in the study, it recognises only the original reference data, and analogously, is not being able to recognise patterns in new data sets, e.g. S. I; S. II.

In order to minimise the risk of overfitting within the learning process done by the NN, the matrix is copied 10 times and also vertically appended to the original matrix. Furthermore, each value of the matrix is added with an individual, artificial noise. In particular, this means that the neural net used within the study now can generalise and classify unknown data safely.

4) Artefact removal in the frequency domain

Disturbances which are noising the frequency signals are so-called artefacts and occur in the majority of recordings. Reasons for artefacts can be caused physiologically, e.g. eye blinks, muscle movement, skin potential, swallowing, or extra-physiologically, e.g. electrode movement, radiofrequency field (Baker 2019). Commonly, artefacts are manually deleted from the signal for analysis from the time domain (see Figure 59).

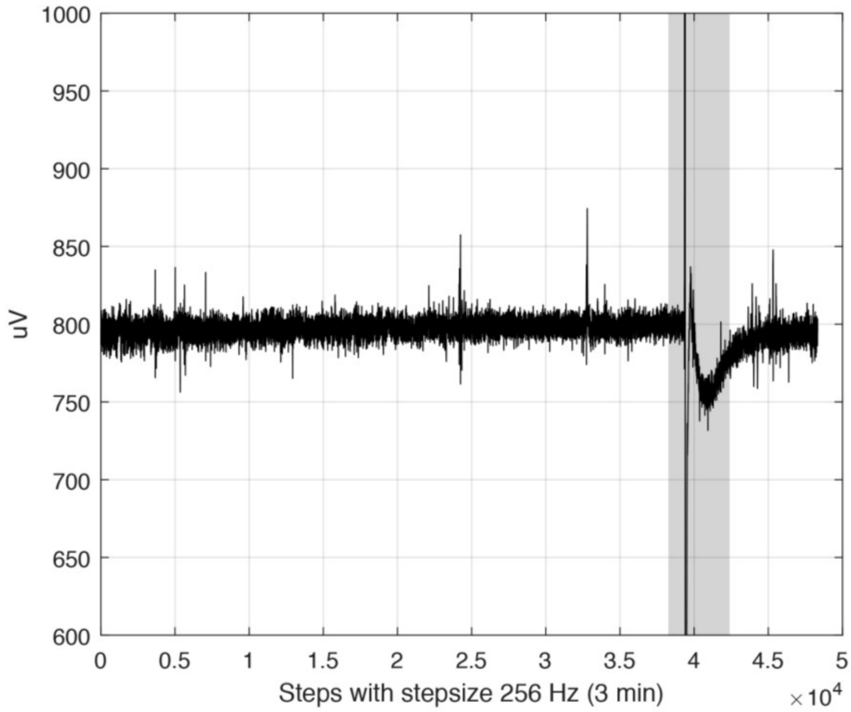


Figure 59 - Artefact removal within a frequency band.

This process takes a long time within data processing. In addition, the deleting cannot be carried out without well-founded knowledge about the evaluation of EEG signals and the occurrence of artefacts. To overcome those limitations, the method presented here is removing artefacts only within the frequency domain. Consequently, this reduces bias through the analyst. Furthermore, this improves the process by keeping more raw data for analysis.

The recordings of all participants have been examined to check if the recordings have been polluted by 50 Hz or 30 Hz noise. If one of the participant's recordings contains this noise, the

50 Hz and 30 Hz frequency within the affected recording and all other recordings belonging to the participant have been set to zero.

The ML classifier method now regards artefacts in the time domain as part of the regular brainwave pattern without labelling the noises as an indicator for stress load. The method developed within this study finally can safely classify the data regarding the full raw signal within the time domain instead of the manually adjusted signal - which is a striking advantage.

5) *Classifying using Supervised ML*

The classifying of the EEG data utilizes Supervised ML as described in 6.3.1. Development of an Objective Workload Detection Method. As shown above, Figure 49, the NN model is trained using Ref. I and Ref. III. Again, Ref. I represents a dataset of a relaxed subject, while Ref. III represents a more likely stressed subject.

The classifier has now been validated by classifying Ref. I - Ref. IV. Finally, the classifier is now able to apply the pre-trained model to classify S. I and S. II. The classifier algorithm successfully indicates the individual's stress level by analysis of their brainwave pattern. The results are detailed within the following section.

5.4.7 The Results

Through the application of the Objective Workload Detection Method within a controlled experiment, the validation of the cognitive strain relief through the WbL System as part of the AIWS was confirmed. Figure 60 illustrates results from data assessed by the *objective* stress measurement method from a participant's neuronal activity and the results from the *subjective* stress measurement method by utilizing the NASA TLX. The results of all participants are attached within the Appendix D. The ordinate shows the subjective mental workload in percentage. The horizontal axis marks the six recordings, Ref. I-IV, S. I and S. II.

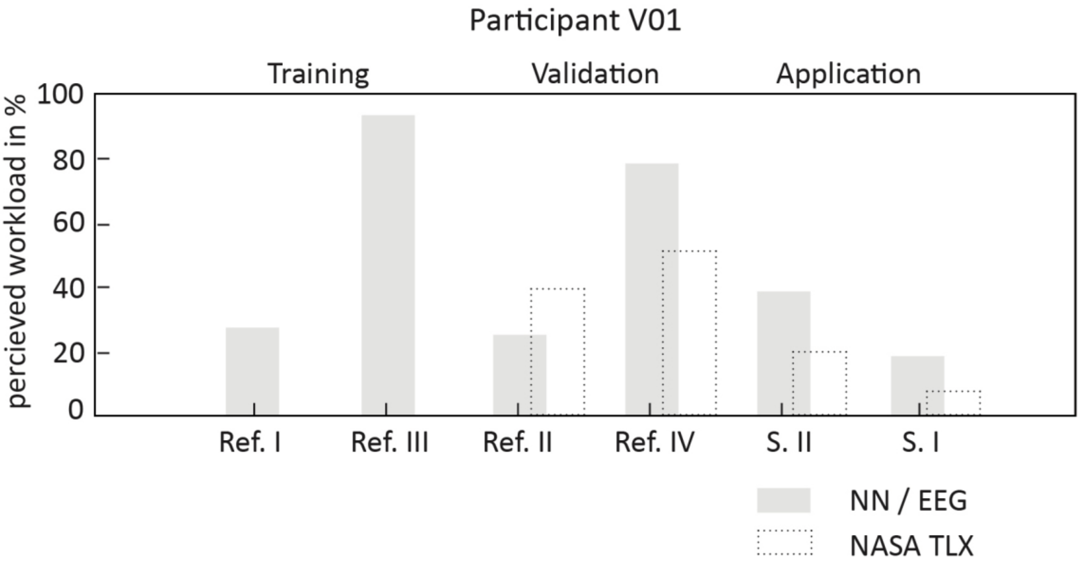


Figure 60 - Correlation of cognitive workload analysis from EEG data and NASA TLX.

Ref. I -Ref IV illustrate the quality of training of the NN. Since the NN was trained using Ref. I and Ref. III, the affiliated recordings of the validation data (Ref. II and Ref. IV) are placed near the value of the training data from the same task. In conclusion, this validates the functionality of the Objective Workload Detection Method.

Within this expanse, the application of the NN allows us to interpret and evaluate workloads of further tasks and the indication of workload between these maximum and minimum limits. In this way, scenario S. I and S. II have been evaluated. Figure 60 shows that the workload was indicated less while the utilization of the WbL System (S. I), compared to the workload indication while working without the assistive system (S. II). Consequently, the most striking result to emerge from Figure 60 is that the WbL System of the AIWS managed to successfully relieve strain during HRC.

Table 14 lists how often the effect of the WbL was experienced as strain relief compared to working without WbL. The results of the two analysis methods are compared.

Table 14 - Evaluation of the WbL's strain relief. Numbers of participants whose measurements indicated strain relief.

Number of participants that showed strain relief

	with WbL (S. I)	draw	without WbL (S. II)	data loss
EEG Analysis (NN)	6	2	0	2
NTLX	8	2	0	-

From the evaluation of Table 14, it can generally be said that S. I was rated better than S. II. What makes the results credible is that both the evaluation via NN and the evaluation with the NTLX contain two neutral evaluations. Here the participant prefers neither of the two scenarios. The two exclusion records are clearly due to problems with the hardware. The structure of the Muse device did not support the accurate fit to a broad variety of head sizes. This led to the detaching of one or more sensors during the session. Those recordings of the two participants, V09 and V10, have not been considered for the evaluation because they showed a very poor recording quality.

The results of the evaluation by analysing the brain waves with the help of a trained NN show that the developed method delivers just as accurate results as the NTLX. If the data of participant V09 and V10 are taken from the statistics, the distribution for EEG analysis and NTLX shows 6 positive ratings to 2 neutral ones. None of the participants found the WbL system to be negative.

(1) According to the evaluation of brain activity, 75% of the participants found the WbL system to be a relief.

(2) According to the NTLX, 80% of the participants found the system found the WbL system to be a relief.

This validates the objective evaluation method on the one hand and shows the efficiency of the strain relief due to the WbL in the AIWS on the other hand.

Although the study has some limitations due to the number of subjects participating[28] and the number of scenarios tested, this study delivers the springboard for further experiments in order to satisfy a sampling distribution.

Taken together, this work managed to successfully develop and validate an event-related, Objective Workload Detection Method by training an NN to interpret an individual's neuronal activity on the basis of an individual's, trained model. Finally, this study demonstrates the strength of the WbL System of the AIWS for cognitive stress relief.

5.5 Summary of Chapter 5

To sum up, the following section resumes the outcomes of the controlled experiment towards enhancing our understanding of HF on workplace design for HRC. The following elements describing the contributions of the concept development, the prototyping, the method development for objective workload detection, and the validation of the cognitive strain relief within the experiment conducted.

Concept development

As a contribution to the flexible manufacturing system, the concept of AIWS for HRC has successfully developed as a flexible hybrid unit design. The concept is based on the derived design criteria for industrial workplaces given in Section 4.6 What Can be Learnt from the Results.

Accordingly, the AIWS considers the three dimensions of HFs in terms of satisfying HF requirements as well as reducing strain while HMI. Consequently, the AIWS delivers a suitable design solution as follows:

Physiological: The AIWS meets the ergonomic standards. Thereby, it satisfies a wide variety of requirements of diverse operators.

Cognitive: The UI-concept including the WbL accelerates the perception of information. Through the indication of the robot's future movement and its status, the WbL supports the conformity with expectations and consequently increases the acceptance toward HRC.

[28] Investigations have been on a small scale due to the interruption by the closing of the laboratory and all public facilities of the Hochschule Wismar, University of Applied Sciences: Technology, Business and Design on the 13th March 2020 for the containment of the COVID - 19 pandemic. The lockdown interrupted the completing of the experiment series, as experiments with participants had been planned on week 12. In order to protect the health of the students participating, this has been accepted as a limitation of the research process.

Organisational: The hybrid unit as an extension of the matrix production enables the industry to transform according to volatile markets with minimal effort and allows a variety of freedoms for the operators, e.g. division of working time.

Prototyping

Moreover, this chapter has presented the construction and prototyping of an AIWS demonstrator that considerably contributes to an exemplary role model for future industrial workplace designs.

Method development and validation

Furthermore, this chapter described the development and validation of an Objective Workload Detection Method. Using supervised ML, that method indicates an individual's event-related stress level. Consequently, the resulting method applies for validation and evaluation of design decisions on interaction systems in terms of HF to give a clear indication of the effectiveness of future HCD investigations.

Method application on the AIWS

Finally, the brainwave classifier has been tested within a controlled experiment. On the demonstrator of the AIWS the strain relief by utilizing the WbL has been investigated. The significant result of the experiment indicates that the utilization of the WbL interface as part of the AIWS reduces strain in HRC.

Chapter 6. Discussion and Conclusion

This chapter discusses the answers to the research questions listed in the thesis; and reviews contributions to the field of industrial design and engineering. Critically, the limitations and shortcomings of this present thesis are consolidated, and further works have been clarified. For illustrating the academic value, this chapter has listed all publications resulting from this research.

6.1 Discussion

Within this present thesis the methodology of the Framework for Innovation has been adopted to investigate the research questions (see Section 1.2) of this thesis. There was a need for adaption to improve/support the applicability of the current framework to develop designs to overcome problem areas within the context of the digitised industry, especially HF within the digitised industry/interaction between operators and joint-arm-robots.

Based on the hypothesis, the adopted human-centred model (see Section 3.2.2) introduces the HF impact, assistance system effort, criteria benefit and methodology support. Furthermore, related activities have been selected and assigned to the relevant phase within the double convergence-divergence scheme.

Based on a need for a method to objectively assess design decisions for cognitive strain relief, a method has been developed within this research. The Objective Workload Detection Method classifies individual's EEG signals. The results have been compared to the subjective assessments using NASA TLX. Consequently, the functionality of the Objective Workload Detection Method has been confirmed.

Finally, the results of the experimental project validated the methodology as the results of the application of the Objective Workload Detection Method demonstrated how cognitive workload can significantly be relieved by an assisting environment.

Relating those findings to the hypothesis (see Section 3.2.1) show that this research indicates all three level of HF impact the workplace design within the digitised industry (Hypothesis 1). The experiment at the design concept-based prototype illustrated how validated design criteria steer designers'/engineers' design practice (Hypothesis 2). Furthermore, the theoretical work within this thesis indicates that assistance systems relieve operators strain that's lead to high acceptance (Hypothesis 3), but further work should be done for validation. The results of the experimental project met the expectations and validated that a method of monitoring/recognising mental load enables design practitioners/researchers to manage the cognitive load proactively (Hypothesis 4).

The study of the HFE has framed the research questions on how human-centred workplace design can support the HRC in the digitised industry including:

1. Analysis/identification of the HF issues and their impact on the workplace design within the digitised production processes, in terms of physical, cognitive and organisational limitations.
2. Discussing how product design can satisfy contemporary industry and its future, in respect of high performance, security and usability. In particular, the physical and psychological interaction with autonomous machines.
3. Investigating multiple HMI and the HRC within contemporary industry.
    a. Interaction with machines, especially in collaboration with robots
    b. Interaction with the networked components of the digitised industry
4. The development of design criteria for workplace design that integrates the autonomous machines in the digitised industry.
5. Prototyping an AIWS concept/demonstrator to simulate a real work scenario of digitised industry, aiming to assess the concept that was developed based on the design criteria.
6. Developing/evaluating an Objective Workload Detection Method concerning subjectively perceived strain.
7. Testing the design criteria on the demonstrator.

The research has clarified the knowledge of engineering and industrial design that related to the HF, including:

- The hypotheses developed based on the secondary research and accommodated the Double Diamond research method in this design-led research.
- The design criteria generated to drive the ideation of a workplace design.
- A concept of the AIWS was prototyped based on the criteria. Aiming to assess if the HCD method can enhance the performance of the HMI.

- An Objective Workload Detection Method was developed, this EEG data-based method can detect individual's stress level by employing the ML algorithm to recognise the pattern of brainwave frequencies, and to be recorded by a mobile EEG device.
- The application of the Objective Workload Detection Method within a controlled experiment validated the cognitive stress relief by the AIWS.

Finally, this research work presented a human-centred framework for designing interaction systems within the context of Human-Robot Teams and how to successfully apply the method to improve strain relieve for operators while working with joint-arm-robots.

This work demonstrated how the cognitive workload can significantly be relieved by an assisting environment.

6.2 Conclusion

(1) The assistive systems will support the HRC within the digitised industry, to enhance the usability, safety, performance, and in particular in bettering the operators' health and well-being. Moreover, all three levels of the HF: physiological, cognitive and organisational will benefit the human-centred workplace design.

(2) Operators working with autonomously acting machines such as robots show a lack of acceptance. This is probably due to the poor system design as it does not support HF requirements satisfactory. Design must address to add value in psychological and physiological strain relief and lead to a build-up of experiences of satisfaction and thus a high level of acceptance of the systems.

(3) Within the digitised industry, the target group is faced with a high complexity of cognitive load while task-solving due to the integration of diverse communication devices as well as the integration of autonomously acting machines. Especially while working in collaboration with a robot, this milieu is characterised as a hazardous environment and correct interpretation of signals is safety-critical. In particular, a fluent interpretation of the robot's status which indicates future movements must be supported by the system design. This cognitive load leads to a strain that negatively affects performance and health and well-being of the operators. Consequently, adequate system design must support rapid data processing by reducing visual signals to a relevant minimum.

(4) Improving interactions between humans and machines, considerable attention must be paid to the design of interfaces. This is not limited to GUI as it also includes the

consideration of holistic system design for HMI, e.g. the workplace environment as an adapting and interacting system.

(5) Product developers and professionally, as designers and engineers, need design criteria, role models and methods for investigation of design decisions. Based on the issues and potential for optimizing industrial workplace design identified within this research, design criteria have been developed in order to overcome the currently existing discrepancies in workplace design for HRC. Furthermore, an overall technique for evaluation of the effectiveness of design investigation focussing on cognitive stress relief.

(6) This work demonstrates how the key competencies of system designers/ engineers are evolving. Key competences from interdisciplinary fields must be addressed in order to react to the rising complexity within industrial environments. This principle can be applied to future challenges arising. Professionals must be able to connect to an equal working team to bundle their knowledge for developments of improved solutions.

The results from this research work indicate that assisting workplace design increase the well-being of the operator, but also indicates that adequate workplace design for Human-Robot Teams supports the acceptance and integration of HRC.

The following section gives a summary of the main contributions resulting from the findings of this research work.

6.3 Contributions

This research fills in the gap of designing industrial workplaces for assisting Human-Robot Teams regarding HF issues in all three levels, physiological, cognitive, and organisational. The methodological framework was adapted from the Framework for Innovation and enables the systematic design and development of the HMI.

Following the adopted conceptual framework, design criteria supporting strain relief while collaboration with joint-arm-robots have been derived and the AIWS and the WbL concept have been developed. This work investigated how cognitive strain while interaction with a joint-arm-robot can be objectively detected and presents a validated answer to this research question: The Objective Workload Detection Method.

Utilizing the AIWS/WbL, the cognitive strain relief of operators working with joint-arm-robots has been validated within a controlled experiment. Furthermore, this work initiates as a reference project with the claim to be a role model that meets the requirements of the digitised industry.

Figure 61 gives an overview of the contributions of this present thesis.

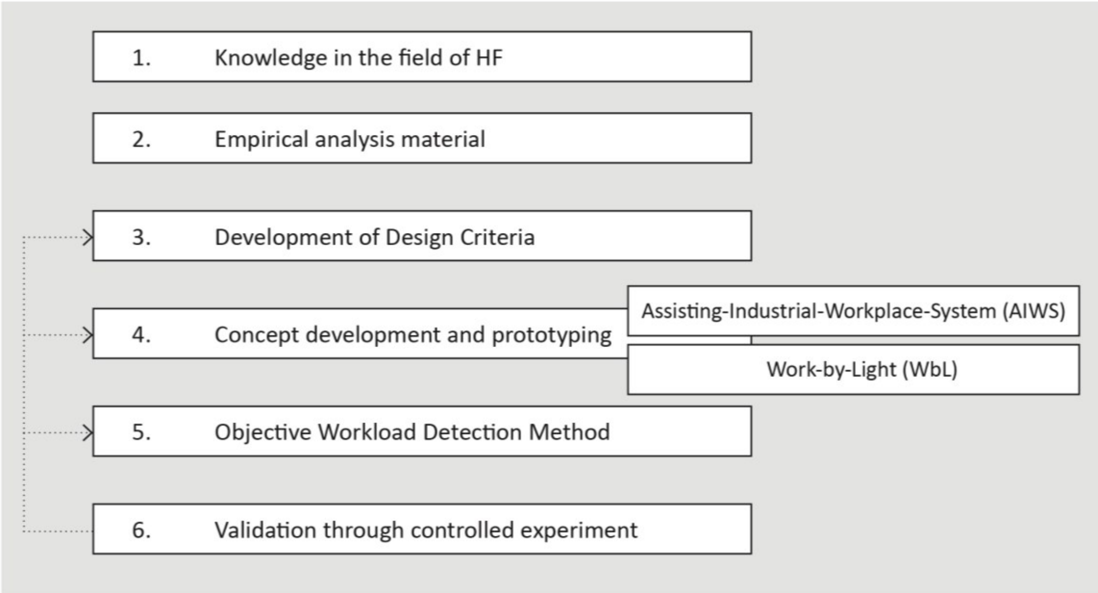


Figure 61 - Overview of the contributions of this present research.

The findings of this PhD research have proved that the HCD will enhance the HMI/HRC in contemporary digitised industry. The contributions have been detailed as follows.

Theoretical contributions

(1) The HCD method enriches the field of the HMI and the HRC research.

(2) The application of the HF knowledge extends the scope of the HCD to the digitised industry.

Practical contributions

(1) The design-criteria specified for improving the HMI and enhancing the performance/acceptance of hybrid Human-Robot Teams has been assessed. This provides designers with a driver/template of workplace design.

(2) The concept of the AIWS design including the WbL solution provides an ideal example/role model for human-centred workplace design in the future.

(3) The development of an Objective Workload Detection Method: the EEG data-based assessment approach, offering researchers an alternative method for classifying individual's brainwave frequencies.

(4) The results of the controlled experimental project validated the design criteria, the effect of the AIWS/the WbL, and the Objective Workload Detection Method.

All these findings may benefit the socio-technical environments to improve the HMI.

Focused on cognitive ergonomics study, the research outcomes may also contribute to other industrial sectors such as:

- Healthcare
- Operational control, e.g. power plants and railways
- Aviation and maritime operations
- Robotics
- Design education
- Spatial/interior design

Likewise, the research findings may support the following fields of research such as:

- Improvement of human interaction with systems
- Increase in human performance
- Minimisation of human error
- Reduction of workload
- Increase in subjectively perceived well-being

In summary, this work is sharing the expertise of the HCD across nationalities, universities, faculties and further benefiting industries. Finally, it is expected to improve individual health/well-being, enhancing companies' competitive ability and promoting the world economy.

6.4 Limitations of the Study

Several limitations in this PhD research were notified by the author, these were related to the 1) data collections methods and analysis, 2) the validation of the findings and 3) the validity and reliability of the controlled experimental project.

1) Data collections methods and analysis.

Multiple concepts of assistive system design may offer various specified/detailed options for the industry. This research utilizes the adapted Framework for Innovation by applying a mixture from qualitative and quantitative research methods related to HCD aspects.

The HMI is complex, and workplaces/environments vary from different sectors within the industry. Differences in applicability or the need to adapt to the relevant field of application might be possible.

2) The validation of the findings.

Furthermore, investigations were on a limited scale due to the interruption by the closing of the laboratory and all public facilities of the Hochschule Wismar, University of Applied Sciences: Technology, Business and Design on the 13th March 2020 for the containment of the COVID - 19 pandemic. The lockdown interrupted the completing of the experiment series, as experiments with 40 participants were planned. In order to protect the health of the students participating, this has been accepted as a limitation of the research process.

3) The validity and reliability of the controlled experimental project

The controlled experimental project at a laboratory set-up appeared to be a reliable method to gain a realistic detection of cause and effect. Since workplace environments are characterised by a complex system of variables, e.g. physiological, cognitive and organisational factors influencing the subjectively perceived quality of the environment, the laboratory environment suited to reduce those factors to an observable number. Moreover, since the controlled environment and the procedure of the experiment was documented, the experiment can be replicated by other researchers.

Although the controlled experimental project is based on a real work scenario of digitised industry, there are also limitations in laboratory experiments.

- The method of the controlled experimental project lacks of realism.
  - Laboratory experiments are characterised as artificial environments. Consequently, not all attributes of the real-world environment can be reproduced.
  - The participants have been aware of experiment and might have changed their behaviour.
- The researcher was responsible for executing the experiment and evaluating the results; this involves the risk of bias. This risk was minimized by anonymizing the data before the evaluation.

Additionally, the Objective Workload Detection Method shows some significant limitations:

- Reference data of the participants show individual fluctuations. Because they came into this experiment with different levels of stress/relaxation. The participants varied in the amount of time to calm and which stimuli they respond to.
- Participants have been only students. It was not possible for operators from industry to participate in the experiment. Therefore, the method lacks of representativity.

The strength of the methods convinced against the limitations. Therefore, the experiment was carried out by applying the Objective Workload Detection Method. Actions have been taken to minimize the detected risks:

- Participants could not meet and therefore not influence each other.
- Participants have been assigned to groups (A/B Test).
- Participants have been selected so that an equal distribution of the sexes was achieved.
- The participants' data were anonymized.

The preparation and implementation of the experiment have been documented and presented in this work. Finally, future researchers will be able to rely on/repeat the experiment.

Assistance systems have become a central critical issue in various application fields. This research shows significant impact as relevant for currently existing workplaces in the industry as well as building up a basis for future research as follows.

6.5 Further Works

Future investigations on assistive systems for supporting the human operator are paramount. To be able to answer currently existing, but also arising challenges on system design, the connection of knowledge from interdisciplinary scientific fields such as engineering, design, healthcare, education and psychology is required. It is recommended, that future research should be undertaken in the following areas:

- Improvement and evaluation of the AIWS
- Transmission of the design criteria on further applications
- Development and application of the Objective Workload Detection Method
- Evolving of higher-education for interdisciplinary design and engineering teams

Orientation for further work on the AIWS is proposed as follows: For the purpose of further work, it is firstly recommended that the remaining parts of the AIWS should be further evaluated for their usability and strain relief. The iterative development is postulated so that the AIWS is successfully established as a digital and manual assistant system. Therefore, elements such as the utilization of ML for the identification of an individual's behaviour on body movements are intended to be a connection to the AIWS operator tracking. A system that independently adapts to assist to the specific operator needs is sought but further, it also must be regulated especially when utilizing AI.

Secondly, the WbL as UI could be further developed towards a communication-tool delivering instructions for task-solving. Therefore, the GUI must regard the design criteria concerning cognitive relief. Further research could address investigating the minimum of required information transported via the WbL to safely deliver instructions. Within a co-creation process research must thereby seek to investigate the adaptation to different skills and preferences of the user. A skilled operator might need less information presented via the UI, than an operator who is more likely unfamiliar with the tasks and the system. Furthermore, the habituation effects must be taken into account.

Thirdly, the AIWS would enable gesture inputs to improve the intuitive interaction with the system. This part has to be evolved while connecting all parts of the camera system for borderless sharing positions of objects and operator.

Moreover, the idea that more than one operator is operating in collaboration with a single robot raises the need for empirical research results. Further research could aim to investigate the AIWS by setting up more than one part of the unit as a demonstrator. This would allow investigating the interaction of several operators communicating with each other while collaborating with one shared joint-arm-robot. It could further be examined what is the maximum number of operators who work together on an AIWS module. In addition, field studies integrating the AIWS within a real-world environment, e.g. manual montage plant would extend insights of user acceptance and usability under real-world circumstances.

The design criteria presented within this thesis have a serious impact for application onto other interaction systems and products. By doing so, it is suggested to adapt to the specific requirements of the intended application scenario. Finally, future works will be conducted in terms of the investigation of new technologies that may be applied to the design of workplaces. This work will serve as a base for future studies on HF for supporting interaction with robots.

The importance of the topic is underlined by research proposals such as the Horizon Europe program, Global Challenges and European Industrial Competitiveness pillar of the European Commission (European Commission 2019). Likewise, the German High Tech Strategy 2015 focuses on the creation of versatile, human-centred structures in factories and networks as well as the development of intelligent, learning production systems, e.g. research program ‘Innovations for the production, services and work of tomorrow’ pillar economy and work 4.0 (Federal Ministry of Education and Research 2019).

Correspondingly, the Objective Workload Detection Method is encouraging. Being able to identify individual’s strain through the interpretation of neuronal activity serves as a strong motivation for future research. Likewise, the method shows high potential to be applied to investigations on psychological stress management. The subjectively experienced effect of creations towards satisfaction in the workplace environment, e.g. a multi-sensorial (visual, auditory, haptic) product and room design can be objectively evaluated.

Further development of the algorithm to classify more than one or two categories is desirable. The detection of intermediate levels would result in the encoding of individual mental states but need to concern framework and considerations of ethics. At the same time, the shortcomings of the present study might be overcome as follows. Limitations of the demonstrator study concerning the low sample size have been previously discussed in Section 5.4 The Assessment of the AIWS concept.

Moreover, further work should focus to improve the Objective Workload Detection Method. A major disadvantage of the EEG device used results from its weak structure that hindered the sensor's positioning on the participant's head and consequently often disturbed the recording of the frequencies. InteraXon. Inc. lately introduced a novel headband that allows the flexible positioning to each shape of participant's head. Future research will improve the utilization of the latest Muse S device for data recording.

To further enhance the method of this research study, future research might improve the algorithm so that real-time interpretation of the neuronal activity advances the evaluation of ERP. Finally, the Objective Workload Detection Method offers the basis for future investigations on design decisions as follows:

a. Examination of acceptance towards movement-rhythm and movement-speed of the robot
b. Examination of acceptance towards a robot's movement speed in connection with the degree of familiarization of the operator
c. Application towards scenarios from hazardous or stressful environments

The collaboration of scientists and the industry in co-creation with the people it affects is paramount and offers a strong tool for overcoming recent challenges. To be able to face recent high dynamic developments challenging how people are working, living, and communicating, future work should focus on bundling of competencies. Facing climate change, pandemics, warfare, high volatile markets and poverty, the potential for the humanization of systems through design is increasing.

Higher-Education of designers and engineers must react now to enable students to adapt in an agile way to cultural changes as well as being able to empathetically pool skills. Besides empowering the team oriented-character of the students the alignment of the courses must be accompanied by a high standard of scientific knowledge in their competence field. Problem-based courses and education focusing on T-shaped competence profiles show strong potential to enable future professionals generating alternative strategies to overcome recent and upcoming challenges for the common good. Therefore, further work needs to be done to establish the value of professional designer and engineer as a mediator of highly diverse teams, enhancing the quality of borderless, interdisciplinary work.

6.6 Publications

This section lists the published studies conducted in the course of this research work. The research conducted within this present thesis demonstrated to satisfies the requirements associated with publication in an academic format such as the following journals:

International Journal Articles (peer-reviewed)

- Ender, Johanna; Wagner, Jan Cetric; Kunert, Georg; Guo, Fang Bin; Larek, Roland; Pawletta, Thorsten. (2019): Concept of a self-learning workplace cell for operator assistance while collaboration with a robot within the Self-Adapting-Production-Planning-System. Informatyka, Automatyka, Pomiary W Gospodarce I Ochronie Środowiska, 9 (4), 4-9. DOI 10.35784/iapgos.36
- Ender, Johanna; Larek, Roland; Guo, Fang Bin. (2021): Design of industry workplaces for human-robot-collaboration. 31st CIRP Design Conference. Procedia CIRP. Science Direct. Enschede. (in preparation)

International Conferences

- Ender, Johanna; Wagner, Jan Cetric; Kunert, Georg; Larek, Roland; Pawletta, Thorsten; Guo, Fang Bin. (2019): Design of an Assisting Workplace Cell for Human-Robot Collaboration. International Interdisciplinary PhD Workshop (IIPhDW). Wismar. DOI 10.1109/IIPHDW.2019.8755412
- Guo, Fang Bin; Yang, Zaili; Jenkinson, Ian; Ender, Johanna. (2019): Changing the Role of Design. In AHFE 2019_Proceedings of the 10th International Conference on Applied Human Factors and Ergonomics. Washington (presentation).
- Ender, Johanna; Guo, Fang Bin; Larek, Roland. (2018): Design of an intelligent workplace system for human-machine-interaction in the digitized industry. Journal of Applied Mechanical Engineering - V7. 2nd Int. Conf. on Advanced Robotics, Mechatronics and Artificial Intelligence & 3rd Int. Conf. on Design & Production Engineering. Valencia. DOI 10.4172/2168-9873-C2-020

Internal Faculty Publications

- Ender, Johanna; Guo, Fang Bin; Jenkinson, Ian; Larek, Roland; Waraich, Atif. (2019): Recommendations designing industrial workplaces for Human-Robot Collaboration regarding Human Factor issues. Faculty of Engineering & Technology Research Week. Liverpool John Moores University. Liverpool. DOI 10.13140/RG.2.2.16706.63683

- Ender, Johanna; Guo, Fang Bin; Jenkinson, Ian; Larek, Roland; Waraich, Atif. (2018): Workspace design for Human-Machine-Interaction. Faculty of Engineering & Technology Research Week. Liverpool John Moores University. Liverpool. DOI 10.13140/RG.2.2.28417.15206

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Appendix A: Publications in the Course of the Research

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CONCEPT OF A SELF-LEARNING WORKPLACE CELL FOR WORKER ASSISTANCE WHILE COLLABORATION WITH A ROBOT WITHIN THE SELF-ADAPTING-PRODUCTION-PLANNING-SYSTEM.

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For some time, the focus of past research on industrial workplace designs has been the optimization of processes from the technological point of view. Since human workers have to work within this environment the design process must regard Human Factor needs. The operators are under additional stress due to the range of high dynamic processes and due to the integration of robots and autonomous operating machines. There have been few studies on how Human Factors influence the design of workplaces for Human-Robot Collaboration (HRC). Furthermore, a comprehensive, systematic and human-centred design solution for industrial workplaces particularly considering Human Factor needs within HRC is widely uncertain and a specific application with reference to production workplaces is missing.

The research findings described in this paper aim the optimization of workplaces for manual production and maintenance processes with respect to the workers within HRC. In order to increase the acceptance of integration of human-robot teams, the concept of the Assisting-Industrial-Workplace-System (AIWS) was developed. As a flexible hybrid cell for HRC integrated into a Self-Adapting-Production-Planning-System (SAPPS) assists the worker while interaction.

Keywords: *Human-Robot Collaboration, Human Factors, Post-optimised Reinforcement Learning Algorithm, Self-Adapting-Production-Planning-System*

KONCEPCJA SAMODZIELNEJ KOMÓRKI ROBOCZEJ DO POMOCY PRACOWNIKA W PRZYPADKU WSPÓŁPRACY Z ROBOTEM W SYSTEMIE SAMOPOCZUCIE-PRODUKCJA-PLANOWANIE.

Streszczenie. *Wcześniejsze badania nad projektami przemysłowych miejsc pracy koncentrowały się od pewnego czasu na optymalizacji procesów z technologicznego punktu widzenia. Ponieważ pracownicy ludzcy muszą pracować w tym środowisku, proces projektowania musi uwzględniać potrzeby czynnika ludzkiego. Operatorzy znajdują się pod dodatkowym obciążeniem ze względu na zakres procesów o wysokiej dynamice oraz ze względu na integrację robotów i autonomicznych maszyn roboczych. Przeprowadzono niewiele badań na temat wpływu Czynników Ludzkich na projektowanie miejsc pracy w ramach Human-Robot Collaboration (HRC). Co więcej, wszechstronne, systematyczne i ukierunkowane na człowieka rozwiązanie projektowe dla przemysłowych zakładów pracy, szczególnie uwzględniające potrzeby czynnika ludzkiego w HRC, jest szeroko niepewne i brakuje konkretnego zastosowania w odniesieniu do miejsc pracy w produkcji.*

Wyniki badań opisane w tym artykule mają na celu optymalizację miejsc pracy dla ręcznych procesów produkcji i konserwacji w odniesieniu do pracowników w HRC. W celu zwiększenia akceptacji integracji zespołów ludzko-robotycznych opracowano koncepcję systemu wspomagania pracy-miejsca pracy (AIWS). Jako elastyczna komórka hybrydowa dla HRC zintegrowana z Samoprzylepnym Systemem Planowania Produkcji (SAPPS) pomaga pracownikowi podczas interakcji.

Słowa kluczowe: Współpraca między człowiekiem a robotem, czynniki ludzkie, algorytm wzmocnień po zoptymalizowaniu, samodopasowujący się system planowania

Introduction

A major reason for the general change in the way of working particularly in industry, is the integration of machines, computers and smart devices [1; 2]. The term digitized industry will be used within this paper to refer to the merge of Industry 4.0 (I4.0) and the Industrial Internet of Things (IIoT). In this context, Cyber-Physical Systems (CPS) evolved as a significant element [1]. These systems contain autonomous operating machines and storage systems and a continuous exchange of information is typical [2]. Tasks within Human-Machine Interaction (HMI), in particular, the interaction with robots will be increasingly integrated into the work process in the future [3, 4].

Currently, there is still a strict separation between workers and robots through fences and safety systems, but further advances of coexistence, cooperation and collaboration of humans and robots have been classified [5]. Within cooperation, humans and robots work towards higher common goals; however, there is still a clear division of their tasks. In Human-Robot Collaboration (HRC) partial goals are also pursued together. To ensure this, the safe and comfortable collaboration of humans and robots is sought [6; 7].

In order to create a human-centred design solution to resolve issues identified within the digitized industry, Human Factors knowledge has been adopted to develop the concept of an Assisting Workplace Cell for HRC to minimise cognitive load, increase the acceptance of the worker and increase the productivity. To develop the concept of an Assisting-Industrial-Workplace-System (AIWS) the three level of ergonomics/ human factors [8] have been investigated:

- Physical level – anthropometrics of the human body and physical interaction
- Cognitive level - psychological perception
- Organisational level - design of socio-technical systems

The concept removes traditional input and output devices such as monitors, keyboard and PC-mouse and employs the surface of the table as an interface that is connected with a Self-Adapting-Production-Planning-System (SAPPS). In addition, to reduce strain, the integration of a post-optimization reinforcement learning algorithm within the workplace system will enable a situational adaptation of the spatial movements of the robot to the behaviour of the worker. The individual adaption of the AIWS to Human Factor needs will improve the well-being of the worker and increases the integration of HRC.

1. State of the research

Bullinger [9], Bullinger-Hoffmann and Mühlsted [10] show that the design of workplaces for HMI needs not only to consider the ergonomic requirements, but also psychological aspects to assist the operator.

Psychological influences have an effect on workers' health and wellbeing whilst working in an industrial environment. Goschke [11] cites the Yerkes-Dodson-law [12], according to which human performance in information processing depends on the complexity of the task and mental activation. A high level of nervous stimulation significantly lowers performance in solving complex tasks. This corresponds to Braseth's [13] suggestion that one of the main issues for designing visual interfaces is to avoid information overloading. The higher dynamics of processes within industry require a permanent interpretation of signals and adequate reactions of the operator. Endsley and Jones [14] outlined how the human brain becomes a bottleneck when the design of work equipment does not provide support for rapid information processing. An adequate design will help to overcome the bottleneck by promoting the rapid reception of information and supporting the interpretation process. Similarly, Bauernhansl [15] draws attention to the flood of data resulting from global networking and ever-improving device technology and concludes that the support of the worker in the production plant is getting increasingly important. In the same way, the BMBF [16], refers to the importance of assistance systems within changing working environments.

Today, the character of industry is changing, and the role of product design has been altered. Sanders and Staplers [17] concluded that industry had been primarily manufacturing-driven and then shifted to technology-driven. Currently, the industry is motivated by the stagnation of the technology push and the user experience appears to be the focus of investigations. In the enquiry of the role of design within I4.0, IXDS Human Industries Venture [18] reports that design improves manufacturing processes when involving all stakeholders early. Accordingly, the user-centred design landscape is developing into an environment of co-creation, where workers are involved in the design process from the early stages [17]. Norman [19] believes that anyone can design, due to their own creative potential. In addition, Steelcase Inc. [20] requires supporting creativity at work so as to create value for business and society. Supporting this potential for creativity and new high-flexible forms of diverse cooperation teams will be the task of workplace design in the future. Given the discussions above, IXDS Human Industries Venture [18] declares that design will facilitate the development of systems to empower skilled operators and non-experts at the same time, and resulting in processes usable for a large number of worker.

Product design is not only concerned with the aesthetic design of the exterior form but also with the proper interfaces for users interacting with the system/environment. With the increasing automatization of the industry, Lee [21] suggests that consideration of Human Factors in design tends to be significant. Contemporary design takes all aspects of ergonomics into account, in particular, the psychological impact on employees.

A growing body of literature examines the features and requirements of the fast-changing production processes within the digitized industry; their findings [22] highlight the new quality of linking production systems as one of the main advantages of the digitized industry. On the other hand, the digitized industry is characterized by dynamic processes with increasing complexity. Approvingly, Acatech [2] comments that an equally important feature of digitised industry results from smart assistance systems which release workers from having to perform routine tasks, instead of focusing on creative and value-added activities. Given a panorama view of research on assistant scenarios, it provides different approaches that aim to support the worker within the industrial environment. In one example: researchers have developed the integration of guidance lights and projections within the workplace environment to instruct the worker [23, 24]. Other approaches focus on the integration of screens or wearables to support the worker in manual production processes [25] or on the interaction with CPS in general [26]. The integration of robots has aimed to reduce the strain of the workload [27, 28]. Sensitive robots facilitate interactions between the CPS and workers through physical contact instead of screens [29]. Furthermore, experts draw attention to machines which are able to increasingly adapt to individual abilities and needs of the worker [29, 30]. Self-learning algorithms process a large amount of data and accommodate the system to different environments [31].

Vogel-Heuser, Bauernhansl and ten Hompel [32] employed the term ***versatility*** to satisfy the requirements of unpredictable commerce changes and to highlight the value of production systems, which can be transformed according to the order situation with minimal effort. These versatile systems are also able to overcome the limitations of traditional production and maintenance systems in dealing with increasing customization of products and small batch sizes. Individual customer requirements can be taken into account and even the industrialized manufacture of individual pieces and production for small batch sizes is profitable [2].

Given these discussions, ten Hompel and Henke [33] comment that a system needs to accommodate its circumstances at all times. The industrial plant of the future must be able to move its regional location effortlessly. Hackl, Wagner, Attmer and Baumann [34] emphasise that in response to technological and economic volatility, the expectations of employees in the 'New Work' have changed.

2. The concept of an Assisting Workplace Cell

The following section discusses how an appropriate product design helps to improve the performance and usability of an HRC-workplace system.

2.1. The Assisting Workplace as a hybrid cell: contribution to the flexible manufacturing

The concept of flexible manufacturing systems enables highly adaptable production [35, 36]. The principal value results from the flexibility of the configurable production cells, where robots are able to handle and add in parts. Tool magazines next to the robot supply the adaptation of the gripper to the work task. Material, parts and further tools are transferred from the warehouses and tool stores to the specific cell, i.e. using automated guided vehicles. Overall, the production is controlled by a decentralized intelligence that connects all parties and is able to communicate, e.g. over the Internet of Things. The workpieces, machines and the process constantly delivers and exchanges process data [35]. These flexible and scalable systems provide an attractive perspective on future production.

Nevertheless, this concept lacks integration of the workers and the adaptation of workplaces for the HMI / HRC regarding Human Factor needs.

2.2. AIWS integration within the production system

The research described in this paper provides a cell for hybrid teams. A cell contains an AIWS for HRC and supports workers interacting with the CPS, e.g. solving of assembly and maintenance tasks (Fig. 1, Fig. 2). The AIWS works as a hybrid cell which is developed based on a real-world scenario from the digitized industry.

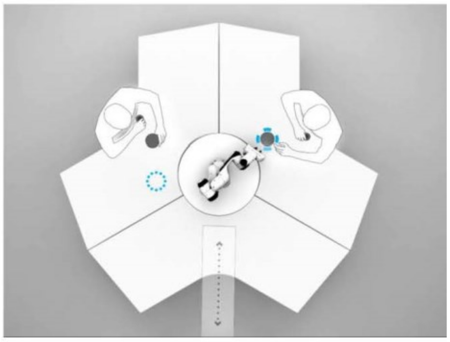

Fig. 1. The concept of the prototype of an assisting workplace for HRC. It includes an integrated Franka Emika robot handling tools and work-pieces which have been delivered by a conveyor belt.

Fig. 2. AIWS - Concept rendering.

Elements of automated production systems within a digitized factory include machines, tool stores, warehouses, manual workstations and HRC-workplaces. These are constantly networked together and sharing their current status. The AWIS extends flexible manufacturing systems by including workplaces for hybrid human-robot teams in order to promote manual tasks (Fig. 3, Fig. 4).

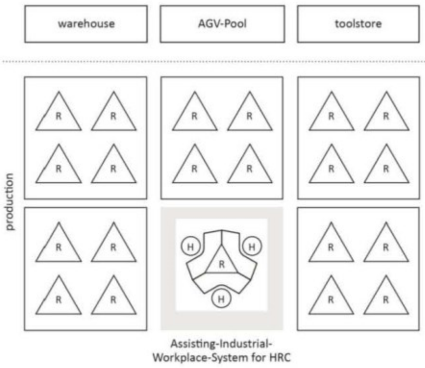

Fig. 3. Integration of the hybrid production cell for HRC as advance of the Matrix Production adapted from [19]. (R-Robot; H-Human)

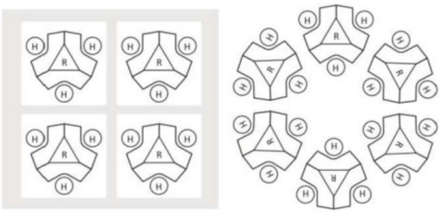

Fig. 4. AIWS - Composition variants of individual cells. (R-Robot; H-Human)

In the background of the assisting workplace, an extended network plan (ENP) controls dynamically the work orders according to the order situation and existing resources [37]. It is a specification of a Self-Adapting-Production-Planning-System (SAPPS) that improves this workflow within the production system. The ENP demonstrates additionally to all steps that are necessary for products assembly, alternatives for several tasks [38]. Fig. 5 visualizes an example of ENP.

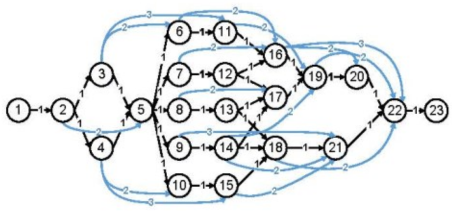

Fig. 5. The extended network plan – an example of an assembly sequence for an industrial production process.

The arrows are weighted with a quantifier x; x = 1 represents the ideal assembly process; all other arrows with $x \geq 2$ represents the alternatives. The ENP algorithm calculates these weights. All needed information like predecessors, successors, preconditions as well as possible alternatives for each job is stored in a database. Whereby, this system is able to respond to constantly changing conditions, e.g. failure of a machine or bottlenecks in the delivery of materials. In situations where alternatives are needed, it provides solutions to the worker which can be done instead of non-available jobs. The ENP algorithm analyses and evaluates the different alternatives based on several parameters such as preconditions, arrow weight and job relevance in the whole assembly process. In the future, the industry will be able to control both incoming and outgoing materials and available tools in tool stores via an automatic and networked storage system include conveyor belts, mobile and autonomous vehicles and robots. The required parts and tools are transferred to the specific homogeneous cells (Machine to Machine) or heterogeneous cells (HMI and HRC). At the workplaces for manual tasks in collaboration with the robot, this robot receives the delivery and handles it to the specific employee. The flexibility of this system is very high-level, including assembly, maintenance, testing, packaging. All work steps can now be performed on the same workbench system of that cell.

In addition, a hybrid form through the integration of machines within a section of the cell is feasible, e.g. two workers and one collaborative robot working with one machine.

2.3. The user experience concerning the AIWS

When starting work, an employee selects a free workplace randomly from one of the many islet cells in the production hall. Based on flexible office-organizational concepts such as the Co-Working Spaces, Collaboration Platform or Desk Sharing, the workplaces of a workbench system cell are freely available to every employee.

When the employee logs into the system through an electronic ID, the workbench will adjust the table height to the individual preferred and previously stored level, and the employee's specific settings such as lighting environment, colour preferences etc. In addition, the system recognizes the employee's skill description and offers suitable work tasks for the current order situation. The CPS adjusts itself independently, to support the specific work task, e.g. the required tools and work pieces are conveyed to the cell and then are supplied to the workplace with the help of the collaborative robot. Subsequently, the employee performs the work steps. The surface of the table serves as an interactive user interface (UI) and guides the employee through the assembly and/or maintenance process. The interface is also motivating during the day, it provides a positive visual response to work assignments completed and reminds the worker to observe break times. The robot assists employees in solving a wide variability of work tasks, for instance through the integrated measuring equipment, the robot could assist with quality-relevant decisions for the reduction of subjective influences by the employee. The broad variety and adaptivity of the end-effectors of the robot offer the possibility of adapting to the requirements of the networked production lines and its current tasks. For example, determining the surface quality can be implemented by scanning the workpiece with a specific effector.

The concept allows a variety of degrees of freedom for the employees and enables and supports the intuitive interaction with the system:

- Free division of working time
- Freedom in choosing the place of work
- Freedom of selection of the scope of work
- Adaptation of the work assignment to specific qualifications

2.4. User Interface concept – Work-by-Light

Part of the AIWS is the development of a communication channel to support the interaction between worker, robot and network. The system will now be introduced by using the term *Work-by-Light (WbL)*.

Derived from the existing Pick-by-Light framework – where operators are directed to particular stock areas via light signals – the WbL system includes a UI that directs work tasks to the worker within the networked plant. The UI utilizes light displays to support operators conducting specific work tasks in collaboration with a robot (Fig. 6). In addition, the light signals give an indication of the future movements of the robot.

Light signals of the AIWS as a communication channel:
- Status display of the robot (active, inactive, error)
- Input and output interface (e.g. work instructions, switching on/ off/ pausing the system)
- Display of the direction of movement of the robot by marking relevant zones on the workbench

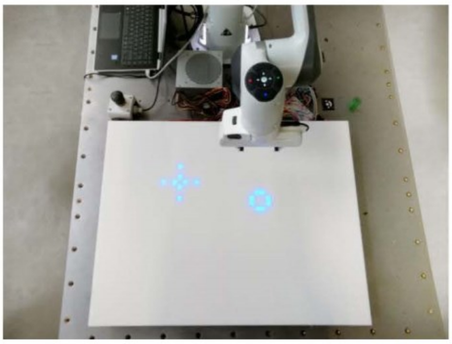

Fig. 6. The prototype of the UI framework which supports the worker during task solving.

In order to minimize the cognitive overload of the worker and to create more free space at the workplace, the table surface itself will be the input and output device. The concept of an innovative and simplified display technology based on a LED-matrix connected with the high performance acrylic solid material was successfully developed. The translucent material is illuminated from below with LEDs. These LED-Matrix can be controlled via a microcontroller. It gets an RGB image from the control computer. The microcontroller extracts the individual pixel information from the image and generates the control of the individual LEDs.

Light signals inside the surface of the table are reduced to the minimum of information to support the rapid processing of the instruction through the worker in order to support the intuitive utilization of the interface and consequently reduces strain in HRC.

Since autonomous robot movement rhythms are generally not predictable, there are still barriers in the HRC that cause stress. The development of the light-guidance system will help the employee to forecast the movements of the robot, and reduce the need for these barriers.

2.5. Set up of the Demonstrator

The assistance system consists of different interconnected components. Fig. 7. demonstrates individual actuators within the concept layout. Based on this structural concept, the pilot workplace for running future experimental studies on user acceptance was already successfully set up at the laboratory of Hochschule Wismar (Fig. 8).

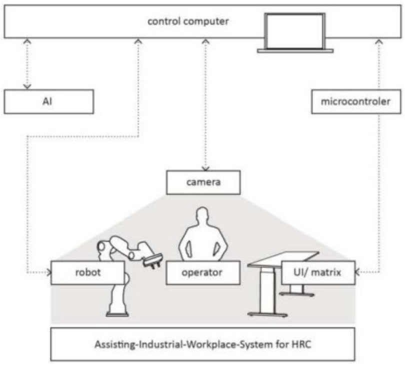

Fig. 7. Structure and communication of the single actuators of the AIWS for HRC.

The operator inputs information through gestures tracked by the common camera-system. The control computer inspects the situation with the camera-system and makes its decision with help of a learned behaviour. If the situation is new to the control computer, it will transmit the situation to an artificial intelligence (AI) component on a mainframe. The mainframe processes this data through post-optimizing reinforcement learning [39] and adjusting the behavioural strategy of the system; after that, the control computer receives the new behavioural strategy.

Fig. 8. Set up of the AIWS pilot workplace at the laboratory of Hochschule Wismar. A camera-system is attached to the ceiling and tracks the workplace.

The control computer generates the robot control program from the learned behavioural strategy. The actions that are suggested from the control computer are positions and/or paths of the robot. The safety functions are still in the controller of the robot.

Moreover, in achieving this aim, the machine learning method will be employed to develop a highly flexible and self-learning robot control program. The program will be able to interact with the employee and production workflow independently, through a model-based learning pattern. The program is also expected to respond adequately to unknown circumstances. Thus, it is imperative that alternative sequences will be learned. The learning process consists of two steps: the real-world process will be simulated with a model and learned (i) offline with the post-optimizing reinforcement learning; then machine learning needs to improve (ii) online for the entire operating time.

The following system elements are derived from the concept and will be developed/implemented by the research group Computational Engineering and Automation (CEA) at the Hochschule Wismar, University of Applied Sciences: Technology, Business and Design:

- Autonomously learning robot control program, which is able to find an order of tasks for the assembly to receive a short production time using with the post-optimizing reinforcement learning [39]
- Secure movements, which do not hinder or distract the worker
- A robot control program, which proactively responds to the individual behaviour of the worker

While learning, the Reinforcement Learning algorithm switches between exploration - acting randomly and finding new states, and exploitation - choosing the best so far known action to reaches as fast as possible the given target. By switching between these two modes, the algorithm learns alternative sequences for solving a problem. While learning offline, the control program always regards the security of the worker within the workplace environment.

After the control program has learned offline, the algorithm has to proactively learn online at the real environment. Even if a path of the robot is blocked by a human or by an obstacle, the algorithm independently chooses an alternative route for the robot to move to the targeted position without disturbing the worker.

However, the movements of the employee will be recorded with a camera-system and evaluated with a standard computer. The analysis of the picture (Fig. 9) marks the position and body dimensions of the worker on the surface of the workbench. Furthermore, images of objects, such as tools and workpieces, can be stored in a database and recognized afterwards within the real environment.

The robot control will use this data. Theoretically, calculating the behavioural strategy of the robot can be completed by any

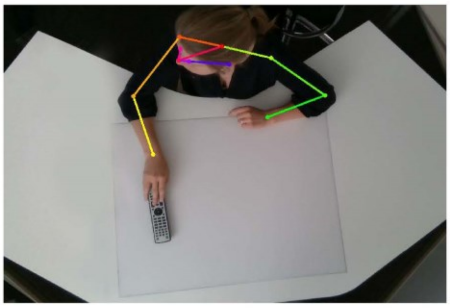

Fig. 9. Camera-Tracking at the demonstrator - The system recognizes the position and dimension of the human skeleton. As a result, the movements of the workers can be detected safely. A recognition and evaluation of gestures would also be possible in the future development - an integration in the pilot system is currently being tested for their relevance for use and implementability.

computer, however, it requires a lot of time for calculation. A mainframe computer is advisable for the calculation to process new/unknown states of the manufacturing process, so the control computer reacts adequately when these conditions are encountered again.

Accordingly, it is possible that the robot control program as well as the UI accommodates itself to the behaviour of the employee using the recorded data and calculated by the control computer.

Connected with the UI, the overall system will be able to accommodate the specific/inconstant behaviour and performance variability of each employee. For this purpose, the robot will proactively adapt the constantly changing movement model of the employee. Since it is impossible for the robot control program to simulate human's behaviour and as it is not predictable, a rigid control program will not be able to complete this task.

3. Summary and outlook

The motivation of the research was to reduce the level of stress, physical and cognitive strain of the operators while working at assembly and maintenance tasks and support the integration of HRC within the digitized factory to increase the productivity. As a contribution to the flexible manufacturing system, the concept of AIWS for HRC has successfully developed as a flexible hybrid cell design.

The concept considers the three dimensions of Human Factors in design:

Physical level: The AIWS with an integrated robot will be able to accommodate behaviour patterns of the employee to satisfy ergonomic and HRC requirements using machine learning.

Cognitive level: The WbL-concept accelerates the reception of information and assisting the interpretation process to reduce strain during the HRC process.

Organisational level: The hybrid cell integrated into a SAPPS and combined with the advantages of the ENP enables the industry to transform according to the order situation with minimal effort and allows a variety of freedoms for the employees, e.g. division of working time.

Considerable progress has been made to the iterative development of the concept, the construction, and prototyping of a demonstrator. Further research will be investigating and exemplifying how the AIWS supports manufacturing tasks within an application scenario from digitized industry. Further works also include investigations of new technologies as smart glass and tablets that can be applied to the design of the AIWS. Finally, testing has been scheduled to organise potential users working on the system. The entire process will be monitored for data analysis and further discussion. Together with feedback interviews of operators will be undertaken to derive and validate the criteria for industrial workplaces design, in terms of satisfying ergonomic requirements and reducing stress while interacting between the use and the system; and resulting to a high acceptance of the HRC.

A considerable relief of the worker's strain is to be expected by the use of the system. This will be validated within a future pilot experiment, in which the subjectively perceived workload is determined.

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LIVERPOOL JOHN MOORES UNIVERSITY

Workspace design for Human-Machine-Interaction

A research of interaction among humans, machines and networks across the digitised industry now and in the future.

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Abstract
Contemporary industrial workplaces consist of operators, computers, robots and autonomously operating machines. The digitised industry introduces various changes of working life through new forms of operation incorporating smartglasses, smartphones and tablet computers. Cyber-Physical-Systems (CPS) including Human-Machine Interaction (HMI) and Human-Computer Interaction (HCI) are increasingly integrated into the working process. The work ranges of robots and operators in manual assembly are progressively fusing – the coexistence will develop towards collaboration. Higher dynamics of processes include additional stress factors and may bring about unexpected consequences to the well-being of the workers. The research will explore the impact on the workers within digitised industry and targets to minimise the strain of the workers within HMC and HCI. Nowadays, a scientific approach for the design of Human-Machine and Human-Computer workplaces within the digitised industry appears to be uncertain. The research intends to develop a holistic approach for the human-centred design of industrial workplaces for interaction with machines, robots and computers.

Aims and objectives
The aim of this design-oriented research is to develop an intelligent workplace system for humans to work within the digitised environment, so that the cyber-physical systems are able to communicate and cooperate to each other and with humans over the Internet of Things.

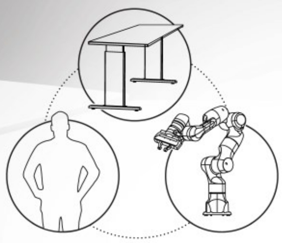

Figure 1. Aspects of Human-Machine-Interaction.

How can a holistic method for workspace design support CPS within the digitised industry in order to create an environment that is adequate for the human needs? Accordingly, the study will place great emphasis on understanding of Human Factors in terms of its physical, cognitive and organisational limitations and their applications to industrial design.

Methodology
The Methodology of this research will be based on the iterative cycle of the human-centered-design (HCD). The HCD-Process is part of the double divergence-convergence scheme, which was first introduced in 2014 by the British Design Council under the term double diamond design process model. "There are four different activities in the human-centered-design-process: Observation, Idea generation, Prototyping, and Testing." (Norman, 2013) Each iteration though the stages lead to a deeper understanding of the user-needs. Therefore, the research will use various analysis approaches. They are structured into following subcategories: covert observation, behavioural mapping, interviews, focus groups, ergonomic analysis and the explorative testing of a conceptual prototype of a novel workbench-system by potential users. The expectations, acceptance and natural reactions of the worker within the HMC will be determined. Feedback interviews will be part of the participatory and iterative design process. This methodology helps to empathise with the workers and to evaluate the proposed design decision.

Approach
A prototype of an novel, exemplary workplace system for the digitalised factory project will be developed based on a real-world-aviation scenario. As part of the research planned, it will be investigated and exemplified how an intelligent workstation system can support the worker during maintenance and manufacturing of airplanes. The workbench system will include a novel interface directing working tasks to the worker within the networked plant. Within the centre of the modular furniture system, the lightweight robot „Panda" (Franka Emika GmbH) will be integrated. The robot carefully supports the worker by efficient assignment of work orders and delivering of tools and work-pieces.

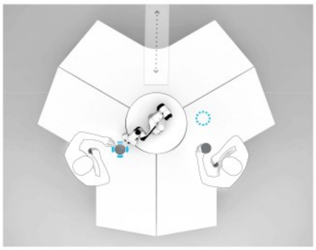

Figure 2. Concept of the Prototype of an intelligent workbench for HMC. It includes an integrated Franka Emika robot.

Conclusion
To increase the acceptance of HMI, in particular of human-robot-collaboration and to reduce the strain of the worker due to cognitive overload, user-centered needs have to be sufficiently considered.

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LIVERPOOL JOHN MOORES UNIVERSITY

Recommendations designing industrial workplaces for Human-Robot Collaboration regarding Human Factor issues

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Abstract

Human-Robot Collaboration (HRC) is increasingly integrated into the working process of the digitised industry. Moreover, workplaces for hybrid human-robot teams are progressively integrated within the production and maintenance systems. A challenging area in the field of the design and integration of workplaces for HRC and Human-Machine Interaction (HMI) within the automated system results from low acceptance towards HRC. Additionally, the strain due to the high complexity of the working tasks combined with inadequate workplace design within the industrial environment leads to several negative effects on the health and well-being of the worker.

A specific method of workplace-design especially for HRC regarding human factor issues is widely not known and will be developed as part of this research work. The methodological basis of the study is the Human-Centred Design (HCD). Within this study, the analysis of Human Factors in terms of its physical, cognitive and organisational limitations has shown significant potential for optimizing industrial workplace design.

This poster summarizes the preliminary results from the analysis phase of the design-based PhD study and uncovers problem areas of contemporary industrial workplaces for HRC and HMI. On basis of these findings, recommendations have been derived and have been used to develop the human-centred concept of an assisting workplace system, which aims to reduce the strain of the workers while interacting with the Cyber-Physical System (CPS) and while HRC. Accordingly, the reduction of strain reduces human error and additionally increases the health and well-being of the workers.

Aims and objectives

The aims will be achieved through the following design-oriented objectives including:

1) Identification/analysis of Human Factors issues and their impact on the workplace design within the digitised production processes, in terms of physical and cognitive limitations.
2) Analysis of how the interaction between human and machine will influence the working environment in the future.
3) Analysis of how digitised production processes change the work.
4) Analysis of how will product design satisfy the industry now and future in respects of high performance, security and usability - particular considering physical and psychological interaction with autonomous machines?
5) Investigation of implementation of multiple HMI and HRC.
   a. Interaction with machines, especially collaboration with robots
   b. Interaction with the networked components of the digitised industry
6) Design of a conceptual solution that integrates humans, machines and networks for the implementation in the digitised industry.
7) Testing and evaluating the proposed design on the demonstrator.

Methodology

Instead of using the technology-centred approach, that emphasized automation technology, this method applies the HCD knowledge to remove barriers between worker and CPS. This design-orientated research is based on an experiment which is validating the prototype of an assiting workplace design; hence the methods proposed in particular at the early stages of the research will follow the IDEO Card process in terms of learn (literature reviews), look (observation/ behavioural mapping), ask (interviews/ focus groups) and try (testing). It starts from a broader discovering, e.g. issues identifications, users' aspirations and expectations of the industry to a narrow solution: the concept prototyping/testing.

Findings

Knowledge in workplace design that is already being implemented in the office landscape to support productivity, safety, well-being and employee satisfaction is not yet considered sufficiently while designing for the industrial workplace environment. Resulting from the revealed problem areas following recommendations for the design of the demonstrator have been derived:

- Reduction of information signals to an essential minimum
- Tool storage and warehouse should be separated from the workplaces
- Development of a flexible workplace cell which delivers workpieces and tools
- Integration of a stand-seat combination with adjustable height of the table surface
- Integration of an ergonomically shaped table surface
- Integration of biologically effective lighting and noise absorbent materials
- Integration of a sensitive lightweight robot for HRC
- Integration of intuitive interface for HMI
- Integration of light signal system, which indicates the upcoming movement of the robot
- Integration of a movement tracking system, to adjust the workplace system to the spatial behavior of the worker
- Integration of a self-learning algorithm to adjust the workplace to specific spatial movements of the worker

The findings gained have been applied to an exemplary prototype concept (see Figure 1.) which has been developed considering the recommendations as mentioned above.

Figure 1. Concept rendering of the demonstrator.

Conclusion

In order to successfully integrate HRC into the industrial production process, recommendations for designing an assisting workplace cell have been derived from the analysis of the revealed problem areas of currently existing workplace designs. In order to validate the demonstrator, acceptance test are conducted starting in the first quarter of 2020.

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Appendix B: Expert views - Interviews

Expert views on robotic and digitalisation

Four questions about the value of workplace design within the digitalisation of the industry

Interview with Dr Elias Knubben,
Head of Corporate Bionic Projects, Festo AG & Co.KG
20th June 2018

How will the relationship between human and machine change the future of our working world?

Our goal at FESTO is it to make technology simple intuitive and easy to understand. The user must have a very specific and concrete benefit due to the integration of an application such as Human-Machine Collaboration. For example, an ergonomically benefit, the incensement of productivity, a highly motivating value through the interaction or a diverse range of the working tasks. As a result, the technology integration won't be regarded as a problem, but will be valued as a significant advantage for the operators. By comparison, people perceive a lane-keeping assistant for the automobile as a very positive application. In the moment it becomes clear that the robot does not rationalize the operators, but supports them in solving work assignments, the potential of collaboration becomes clear. I am sure people and robots will work hand in hand in the nearest future and the operator will benefit from the improvement of working conditions.

How do you imagine an implementation of Human-Machine Collaboration within the digitized industry?

The potential of so-called collaborative robots and tele-manipulation has been recognized. Operators will have identical workspaces with robots and autonomous machines. Therefore, the design of future working spaces must be correspondingly flexible.

Our pilot project BionicCobot is specifically design for Human-Machine Interaction and it is based on the human arm not only in terms of its anatomical constructions. Consequently, the movement of the robot can be intuitively understood by the operator. The developers have technically implemented the principles of agonist and antagonist on the BionicCobot in all seven joints. Like its biological role model, the pneumatic lightweight robot convinced by high flexibility and highly sensitive movements. The system of the BionicCobot allows to be used without protection cage, thus making a safe Human-Machine Collaboration possible. For the design concept of the BionicCobot, the learning curve of the development team ran iteratively. We use prototyping to test our bionic-inspired concepts and for the prototypical implementation of initial ideas. Testing provides us with information for further necessary adaptions for increasing the usability of the system.

The certification and standardization of collaborative robots in general are rudimentary. There is still much work to be done.

While developing such a pilot project, do you follow certain design guidelines or methods for designing workplaces for Human-Machine Collaboration?

Our design philosophy here at Festo is always visionary, sympathetic and understandable. Of course, technical specifications, such as the hose guide of the robot, motors, drive systems, and rotary and swivel axis dictate certain cross sections. The functionality defines the form and is supported by the colour in accordance with the specifications of Festo's Corporate Identity Guidelines.

As a result of a successful product development, the design communicates its usability and supports the interaction. Therefore, the BionicCobot for example, communicates via light signals at its joints, in case an error has occurred.

How product design satisfies the industry now and future in respects of high performance, security and usability, in particular physical and psychological interaction with autonomous machines?

The understanding of product design in our team is of a highly conceptual nature. As designers we are developing concepts for interaction and are not only creators of covers. Therefore, Festo's design team approaches a question conceptually and with highly agile development methods.

We developed solutions inspired by nature together with scientist, students and external partners. We want to learn from nature and we want to fascinate through the use for technology, to inspire people and we want to pre-develop products in the field of industrial automation. In order to enhance the productivity while developing our concepts, the process is done by an interdisciplinary team. In our department at Festo, the different experts are sitting next to each other working closely together: computer scientists, designer, biologists and control engineers. This is not only much fun; you also can learn so much from each other. It is highly motivating and you will get a much deeper, better understanding of the context of the product development. During the concept development it is further important to consequently zoom in and out, to think in variations and iterations. Therefore, we have generalists in our team, who mind the big picture, and specialists, who dive deep into technical problems. The team has the playground and the freedom to create better solutions together.

We really often start by using prototypes at the early stage of the product development. This kind of 'hands on prototype' is really helpful for generating fast and successful insights of possible concepts. The interactive approach is important for acceptance and implementation of products in the future industry. We also have to ask the customers, if we are on the right track – thanks to rapid prototype, solutions can be tested and can be used to get direct feedback from industry. Afterwards, we finalise and adjust the concepts to the needs of the customers.

It is so important to concentrate on the essence of the concept. It is not only about the features a product has, or doesn't have. Even if we are so fascinated by new technologies, all the advantages, maybe the risk as well, it is important to have the potential in mind and what can grow out of an idea. Finally, I want to point out how important it is to think big, discuss ideas and find other in the world to collaborate.

Interview summary released for publication by Dr Elias Knubben.

Expert views on robotic and digitalisation

Four questions about the value of workplace design within the digitalisation of the industry

Interview with Dipl.-Psych. David Kremer,
Competence management, Fraunhofer IAO
13th December 2018

How will the relationship between human and machine change the future of our working world?

The possibilities of flexible production, especially for the production of individual products/batch size 1, which would be possible by integrating a robot into digitized production, are largely unused today. This is not due to the limited spatial conditions of the production plant, which speaks in favour of the use of (lightweight) robots. Rather the elaborate setup of a shared workplace for Human-Robot Collaboration, e.g. planning, construction, safety, ergonomics, documentation, legal aspects, know-how structure to Human-Robot Collaboration forms the main hindrance.

Also, human creativity as a valuable potential is not used yet. Instead of rationalizing operator out of production, flexible ways should be created to actively integrate operator into the production process.

A major challenge integrating robotic assistants results from operators perceiving the physical proximity of the robot as unpleasant or frightening. Although this can be overcome by qualification programmes and habituation, currently the majority of Germans still react to cooperation with robots with ambivalent feelings. However, if the robot supports the operators solving tasks, e.g. by taking over ergonomically unfavourable movements, the operators recognize the positive effect very quickly and a high acceptance increasement of the robot assistants is clear.

Moreover, in practice of the working world in Germany there are just a few robots characterised by a human-like appearance, be it a face or a human-like shape. It is important to us that the robot is considered a machine, a tool. An adaptation of the robot through the use of a human-like design character would disturb this perception.

Possible, positive scenarios of the potentials of Human-Robot Collaboration are shown in the publication: Zukunftszenarien der Mensch-Roboter-Kollaboration im Jahr 2030.

How do you imagine an implementation of Human-Machine Collaboration within the digitized industry?

The Fraunhofer Project AQUIAS supports people with and without restrictions in the joint completion of tasks. At the beginning of every research project for the integration of robotics, our team searches for a suitable application scenario. If a specific problem area is found, the various functions of robotics offer flexible application possibilities. Important while integrating a robot into a system is always the amortization, e.g. how quickly the system is able to be used profitably in production and covers its own costs. If a suitable layout for integration into a working environment is found, it must be able to adapt to the constantly changing requirements of the working environment, technology development and the nature of the work orders itself. This is a challenge for any workplace system for human-robot collaboration.

While developing such a pilot project, do you follow certain design guidelines or methods for designing workplaces for Human-Machine Collaboration?

We use CAD, VR and Cardboard engineering to early prototype concepts. This allows the team to make intuitive decisions about how to set up and design workplaces. For each project, the development team reviews individual risk coverage - this is particularly important for designing workplaces for people with disabilities. Potential sources of danger are identified, and concepts are compared to their specific suitability on the basis of exclusion and evaluation criteria. Participatory design techniques include prototypical setups and employee workshops - together with the end users, we develop models for workplaces which include integrated robots.

How does product design satisfy the industry now and future in respects of high performance, security and usability, in particular physical and psychological interaction with autonomous machines?

The development team at AQUIAS consisted of psychologists, curative education nurses, computer scientists, engineers and business economists. Within this highly diverse team, goals were intuitively pursued, and the development process was driven forward together. Due to the various qualifications of the team, the cost-effectiveness of deploying a robot, the costs of implementation, the creation of the layout in consideration of the ergonomic requirements as well as the inclusion of operators, e.g. with special limitations has been realized in parallel. Moreover, the interdisciplinary work will increase in importance for engineers and designers.

Communication between the members of the team is the basis for successful project development.

Interview summary released for publication by Dipl.-Psych. David Kremer.

Expert views on the changing role of design

Four questions about the evolving role of design within the changing requirements of the industry

Interview with Dipl.-Des. Andreas Hackbarth
16th July 2020

Please point out your position as a designer. How was your personal development?

Andreas Hackbarth starts his answer with a quote:

'Today`s clients commission either a name – star designer as a brand mark – or a plain unsophisticated service. But not a labour of love' (Jens Reese/page 75/ Design is attitude)

To follow: my know-how including my love affair with design.

To establish the position of my thoughts please consider it is just a facet of many alternative ways how to do design. For example, in my case it`s about a product designer employed in big in-house design departments for all of his professional life. Which is to say: there is an endless number of variants. To vary from single designer, small agencies to big design departments specialized in automotive, transportation, user interface etc. I put a lot of emphasis on this because cultural background and professional experience differ strongly from one designer to the next. During my business life I noticed that you are a 'child of your time'. Sounds like a platitude but this awareness is inevitable. It hit me when I was in front of a glass display case showing our tools of the trade (ruler, slide gauge, compasses, mine pen, transparent paper, razor blade), the tag on the glass cabinet reads as follows: 'drawing utensils, late 20th century'. Hey, I just worked with those!

I did my academic studies of design at the Academy of Arts/HfbK Hamburg (1975/1981) with professors Rosenbusch (architect & designer), Raacke & Schild (both of HfG Ulm) and Rams. The underlying cultural imprint caused by the 'Ulm mind-set' was very subtly in the beginning but working with Rams I took in his minimalism by implication. This part of your life is called 'the formative years'. The space of time in which you are shaped. To be a designer – what a nice allegory!

The Academy of Arts/Hamburg offered a big advantage for my personal conditioning. All departments were under one roof: you could learn about colour theory from the artists, likewise how to draw act or attend graphic printing courses. You could help architects to build architectural models and visit their lectures. Listen to guest speakers like Beuys & Christo.

There were theorists like Brock or practical men like Rochelt. All encounters were experiences which opened my eyes and broadened my horizont. Priceless to form a self-contained personality who wanted to make a living with design.

Which changes regarding the education of industrial design did you live to see?

In 1975 the application was exclusively by submitting a portfolio of your work. There were no interviews, no assessment – a bit like a lottery! 60 candidates, 6 chosen ones. In my time there were no intermediate exams and no defined number of semesters needed to complete your studies, total freedom! A lot of students could not handle the concept and the estimated number of academy dropouts without any perspective was horrendous. You had to learn how to structure yourself and sooner or later you had to be prepared to register for the final exam. Only individual products were designed, rarely systems because there was not sufficient knowledge and just minimal budgets in order to tackle complex concepts. This kind of training was adequate to turn out ‘lone fighters’. Teamwork was extremely rare in those days. This is important to remember because in the eighty’s companies needed exactly this kind of single-minded individuals. So, in a way I was trained perfectly to fill out the future job.

Johanna, you know much better than I do how design training works nowadays: school-like, limited time schedules, professors and universities certified, everything is digitised, interdisciplinary teamwork and networking etc. – but will it create multifaceted personalities? Currently a lot of designs appear to me (born in 1953) rather two-dimensional and smoothly polished. Not to say: superficial. As Dr. Lengert said: ‘the unbearable shallowness of appearances’.

How should the training of design students be adapted to the changing demands towards designers?

Once again, I would like to give you a two-part answer: in retrospect and how it should be in an ideal way in 2020.

Just once in 1994 I made a unique attempt and I applied for a professorship at Hamburg`s Academay of Arts in succession of Professor Raacke. This initiative was provoked by Rams because he wanted his design approach to live on even after his retirement in 1997. My application lecture targeted a gap in the design education at that time. Until Rams joined the Academy of Arts there was no practical relevance whatsoever. Even to participate in design competitions was a no-go! After 11 years in professional design I could offer to close this gap, thanks to my know-how. But only in Hamburg`s Academy of Arts because I was still very aware of the deficits regarding the design training. After my lecture the head of the model making workshop told me: super interesting but here we don`t know what you are talking about! The design department was guided by Friemert to a modern arts & crafts attitude and in the years that followed they only took designers of unique products (furniture/glass) on board. Which was legitimate but you could not call this program of study ‘Industrial Design’ any longer. Regarding this context my input would have been useless and with hindsight it was fair to both sides that we did not join forces. This episode is to demonstrate how the future of design training was in 1994, at least in the Academy of Arts in Hamburg.

As for the current training of design: once again you are better qualified to answer. I think most arguments are well known by now. More international cooperation (even with unloved marketing), more international academic exchange (obligatory semester abroad), more offerings for international studies (bachelor/master), dual studies in design (sponsoring by companies?). Maybe it already exists – I´m no longer up to date. A smart forecast by Belgian designer Raf Simons in SZ magazine, #16/2020: ‘What it`s all about in future: how people will establish relations, which options will open up for us as a society’. And vice director Magda Seifert/Design Biennale Porto (Portugal) in SZ /30.10.2019: ‘This generation is not connected by a collective style but by shared crises and by their network, where country`s frontiers do not matter any longer’.

Another inherent part of any training presently has to be the matter of resources. In my professional life until 2018 it was noticeable that most projects of our interns took the topic of resources into consideration. The early and endlessly repeated statement of Rams concerning responsibility in regard to the environment seems to bear fruit very slowly. Taking into account his all-encompassing minimalism it represents a logical self-evidence. Nowadays it is prominent everywhere: i.a. the Dutch Design Studio ‘Formafantasma’ with its research project ‘how design can be an important factor concerning a responsible conduct with resources’. I think there are innumerable examples but instead of wish-wash a firm expression of will must be worked out and exemplified. Dr Lengert: ‘Credibility arises from the harmony between what you say and what you do’.

Interesting as well: the students of my friend and ex-colleague Professor Hatto Grosse/Cologne are supposed to design ‘trust’. Not as a formally attribute to optimize a product but as an attempt to integrate an immaterial moral concept into the design process. Thanks to a task like this a student can try himself, not in terms of learning about product semantics but to centre yourself in the future working field of design.

Which transformation regarding the importance of design have you detected while being within the job?

In my professional years (1983 – 2018) there was one essential caesura. In 1997 the last drawing board was sent into retirement. That is to say 14 years were analogue design with many many two-dimensional sectional drawings and a close collaboration with a model maker. Similar to a marriage symbiosis, door to door, to transform a sketchy idea with the help of dimensioning into an understandable and tangible mock-up. Drawings as well as modelling were all handmade. Depending on the quality of the 'marriage' it was a very satisfying way of form finding. In design departments like Braun and Siemens renderings were 'fake pics' and not opportune. There was always a proper budget to build 1:1 mock-ups. Focus was mostly on solitary products (telephones/lamps) but also first attempts to design systems (tableware Lufthansa with Braun, telephone systems with Siemens). The following 21 years were digital, e.g. design with the help of computers, presentations via CAD-renderings, the final data was used by the model shop to produce mock-ups. Due to the increasing complexity of tasks & solutions teamwork became acceptable (= essential) and suddenly there was a big need for designers and application experts of CAD. First digital programs came from engineering and had to be learned by the designers or had to be adapted to the needs of design. Finally, from now on the designers were on a par with their dialogue partners from engineering. In the 21th century the tandem designer/engineer turned into a triumvirate: + marketing!

In the beginning with Siemens all products were industrial goods (medical equipment, nuclear power plants, street lamps, radio communication units, telephone systems etc.) but starting in 1992 consumer products like mobiles were added to the portfolio. This was a new challenge for us German industrial designers and new colleagues from foreign countries were brought in to provide expertise how to design consumer products. A specific Corporate Design (CD) used to be part of our daily design task regarding long-lasting industrial products. But now marketing was in the driver`s seat and changing tastes and fashions had to be considered. Our tool (Corporate Design Guidelines) and our mandate to produce and to control design quality lost relevance internally. Inevitable this mode of behaviour includes a certain arbitrariness that contradicts serious design. I met this tendencies again later with BHS/'white goods'. Here again marketing wanted to offer solutions for each and every costumer request. After all BSH tried to organize the varying requirements by creating a wide brand range and therefore it was possible to offer something suitable for each country and target group. With the help of price regulation, product equipment and design differentiation.

If I should illustrate the transition of my years in design by modifying the title of Jens Reese`s book it would look like this: 'the engineer and his designers', later 'the engineer and the designer' and finally 'the engineers, the designers and marketing'.

Judged by my today`s point of view and experience the actual part of a designer is less about a frictionless cooperation with construction and marketing – that goes without saying. But: contemporary input of a designer must be to represent the 'all-rounder' in collaboration with the real specialists. Interesting: there is a common understanding with Dr Knubben/Festo and his definition of allrounders and socialists. Of course, the designer is an expert as well but he guarantees the value of an attitude, common sense and up to date knowledge of soft skills (cultural influences like art & fashion etc.). The designer is supposed to think outside the box and he can be very enriching to generate useful products. Very often he is the only one to attend different working groups - like a bee flying from one blossom to the next. A smart company detects this virtue and offers the vital free space for the designer to develop and to convey sensory skills. But it requires confidence on the part of the company and this is in short supply the way I see it.

Nowadays in order to structure highly complex operations there is a control madness called PEP (ProductDevelopProcess). Depending on the product and its product life cycle each and every step is defined by milestones in advance of 3 – 5 years. Which input is needed when and where? From kick-off to design acceptance test, from usability test to pilot series and the date of product launch. A precisely timed sequence is assigned to the designer, his performance is requested and 'installed' only in this defined time window. The 'soft' quality of the 'all-rounder' mentioned above is not recognised and not used in an ideal way – what a pity! Quote by Dürrenmatt: 'the more planned people act, the more effectively chance will hit them'. I noticed this countless time because due to long lead times (PEP) various disruptive factors popped up which nobody from product management had on their radar. In certain circumstances collapses like corona or world-wide conflicts offer the possibility to adjust methods to reality. Megan Dinius: 'In past years many companies emerged strengthened from economic crises instead of being ruined. They started to think about their products in a different way. A constant component of every in-house restart: a clear commitment to design'.

It is a major challenge for a designer to live attitude and aspiration in his professional life. Not just during the cooperation with the specialists but unfortunately also in daily work with fellow colleagues in design. I never met a designer who claimed NOT to have an attitude. But facing adversity it is a troublesome road to stay true to yourself, to exemplify your position and to push your ideas. Very few colleagues were able to bear comparison.

Again Raf Simons: 'Designers like Joe Colombo didn`t think from one design to the next. They preserved a social and holistic point of view. That is what we miss today. As designers, in spite of being confronted with problems, we should not lose our claim to design a better world'.

Interview summary released for publication by Dipl.-Des. Andreas Hackbarth.

Appendix C: Interview Guide - Focus Groups

Interview guide: Focus Groups

Date/Datum:

(1) *What is your job role and sector of the industry?*
In welchem Sektor und in welcher Funktion arbeiten Sie aktuell?

(2) What is the level of automation of your business (production, assembly, maintenance, etc.)?
Wie hoch ist der Automatisierungsgrad Ihrer Firma (Produktion, Montage, Wartung etc.)?

Manually *manuell* □□□□□□□□ highly automated *Hoch automatisiert*

(3) What is the future variability of orders to process?
Wie hoch ist in Zukunft die Variabilität der zu bearbeiten Aufträge?

manufactory *Losgröße 1* □□□□□□□□ *mass production* *Massenfertigung*

(4) How do you rate the flexible management of personnel capacity for your company?
Wie wichtig wäre eine flexible Steuerung der Personalkapazität für Ihre Firma?

(5) How many employees are currently working on your shop floor (e.g. production, assembly, maintenance)?
Wie viele Mitarbeiter arbeiten aktuell in der Produktions-, Wartungs- oder Montagestätte?

(6) How do you rate the role of the human work within your shop floor (e.g. production, assembly, maintenance) for the future?
Wie hoch priorisieren Sie die menschliche Arbeit innerhalb Ihrer Produktions-, Wartungs- oder Montagestätte für die Zukunft?

(7) Does your company use robots? *If yes, what kind of robot?*
Nutzt Ihre Firma bereits Roboter? Wenn ja, welcher Art?

(8) *How do you rate the acceptance of the operators over the robots?*
Wie hoch ist die Akzeptanz der Werker gegenüber den Robotern?

(9) *How will the relationship between humans and machines change the future of our working world?*
Wie wird die sich verändernde Beziehung zwischen Mensch und Maschine die zukünftige Arbeitswelt beeinflussen?

(10) *How do you describe the implementation of Human-Machine Collaboration within digitized industry?*
Wie stellen Sie sich die Implementierung von Arbeitsplätzen zur Mensch-Maschine-Kollaboration in die digitalisierte Industrie vor?

a. *While developing pilot projects, do you follow certain design principles and/or methods to design workplaces for Human-Machine Collaboration?*
Nutzten Sie spezifische Design-Richtlinien oder Methoden zur Gestaltung von Arbeitsplätzen zur Mensch-Maschine-Kollaboration?

(11) *How does product design satisfy the industry now and future in respects of high performance, security and usability, in particular physical and psychological interaction with autonomous machines?*
Die physiologische und psychologische Interaktion mit autonomen Maschinen beeinflusst vermehrt die Werker. Als Konsequenz verändern sich die Anforderungen an das Produktdesign in Hinblick auf Sicherheit, Benutzerfreundlichkeit und Unterstützung von High-performance-Prozessen. Was sollte das Produktdesign leisten, um

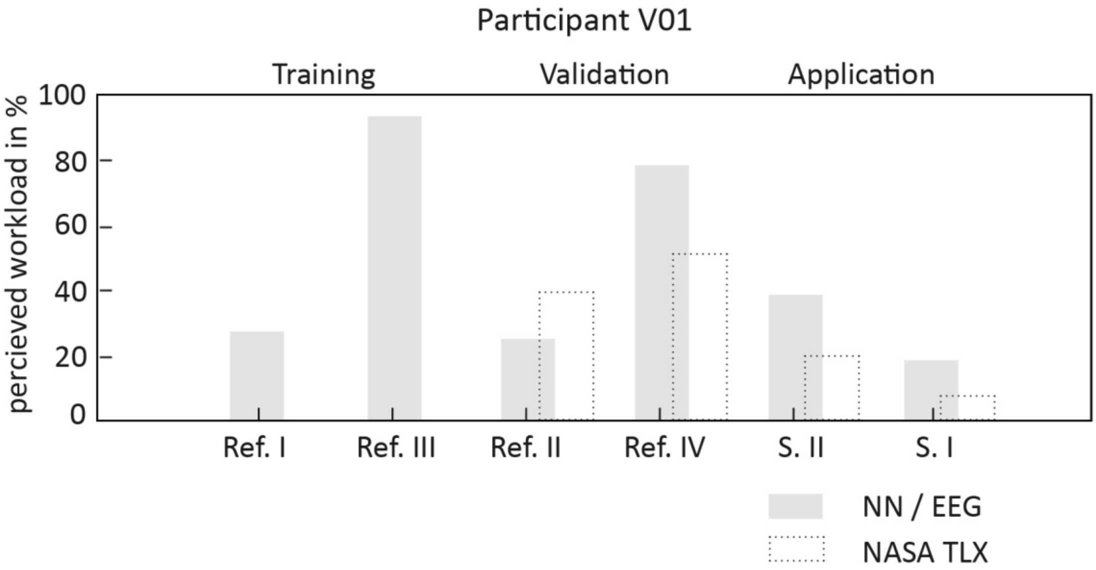
den Anforderungen der digitalisierten Industrie heute und auch in Zukunft zu begegnen?

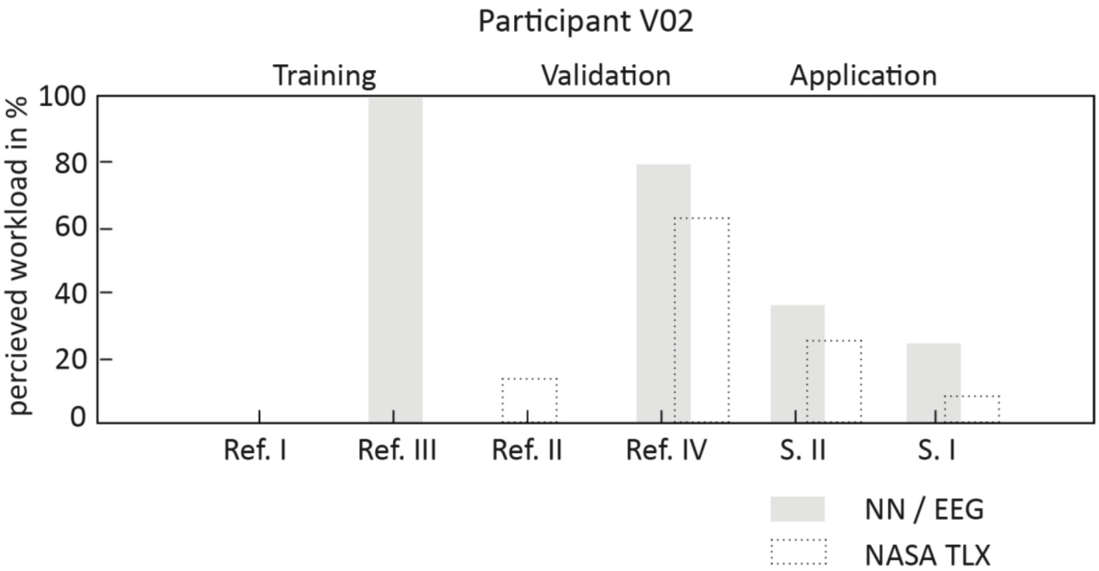
Released for evaluation and released for publication within scientific work by:
Freigegeben zur Auswertung und Publikation im Zusammenhang mit der Erstellung wissenschaftlicher Arbeit:

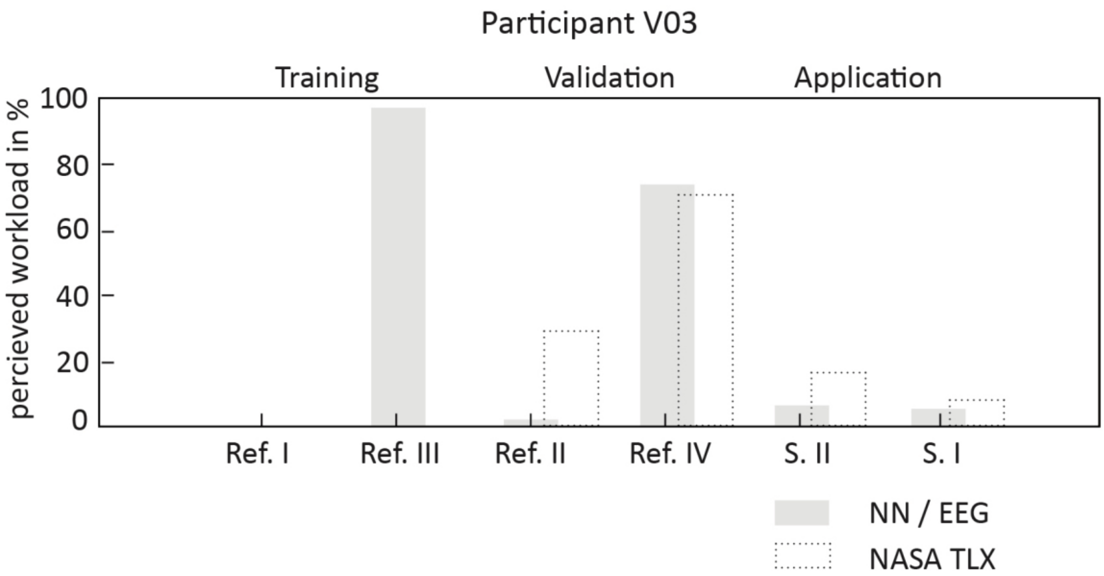
place/date/signature
Ort/Datum/Unterschrift

Name (block letters)
Name (Druckbuchstaben)

Appendix D: Results of the controlled experimental Project



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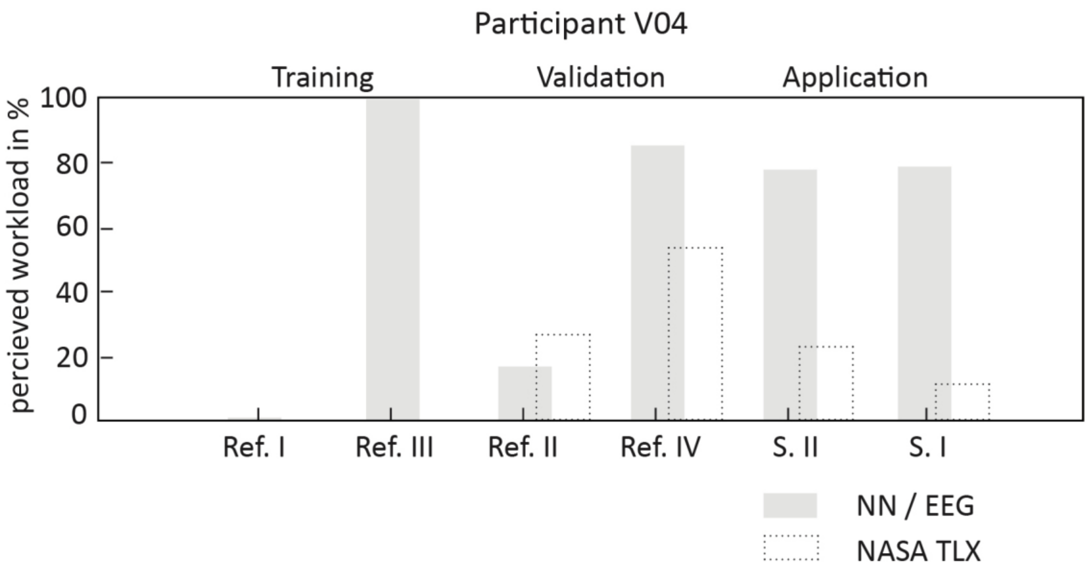
S. II
S. I
NN / EEG
NASA TLX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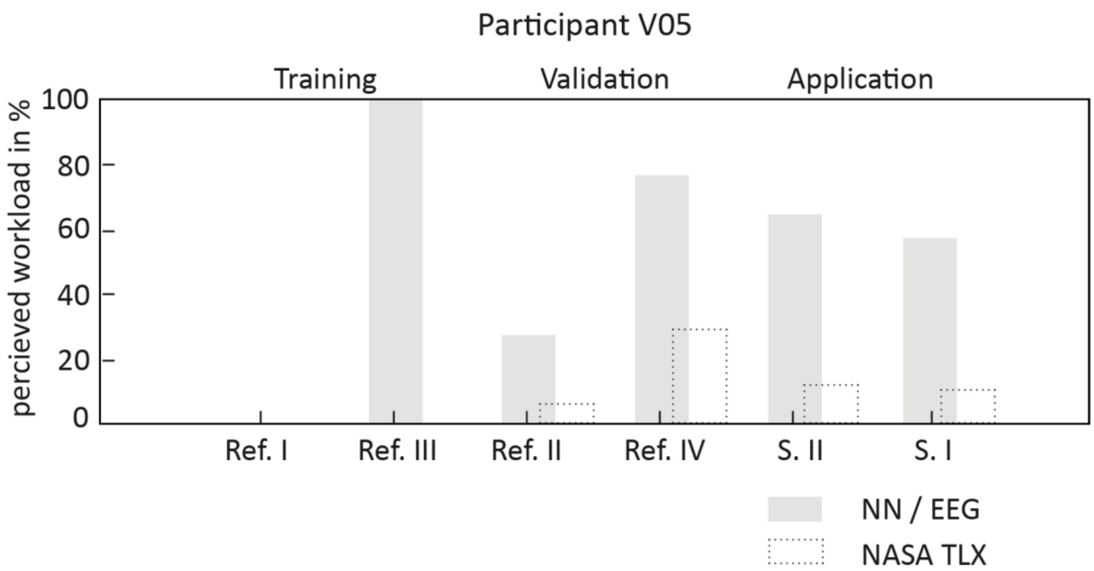
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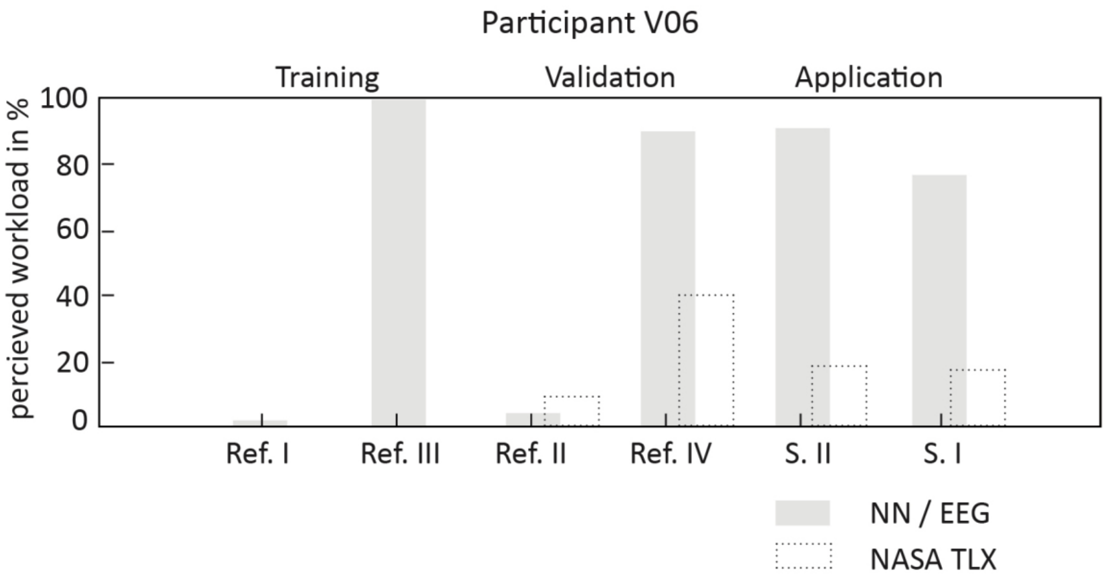
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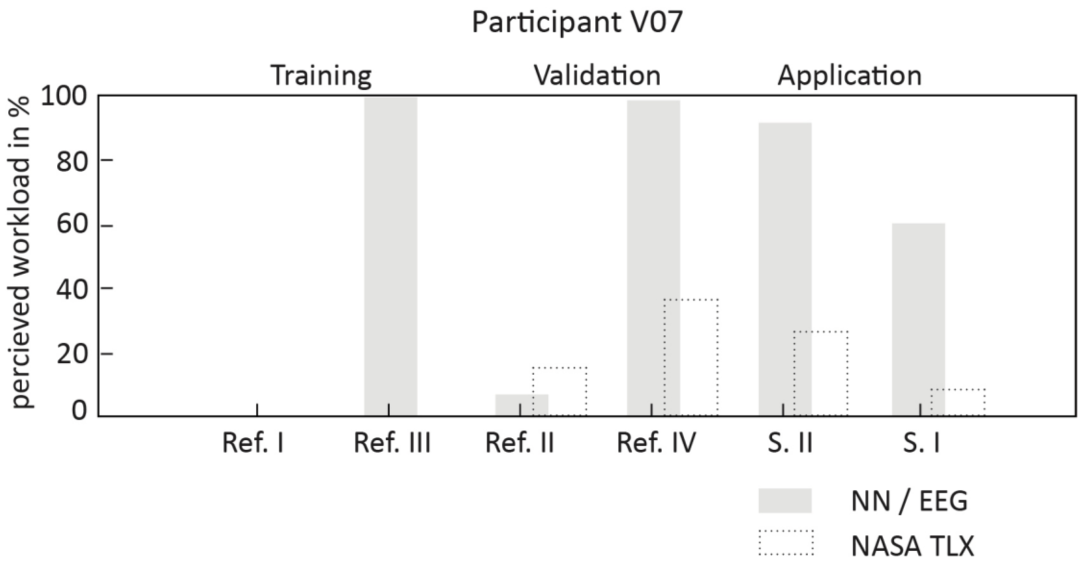
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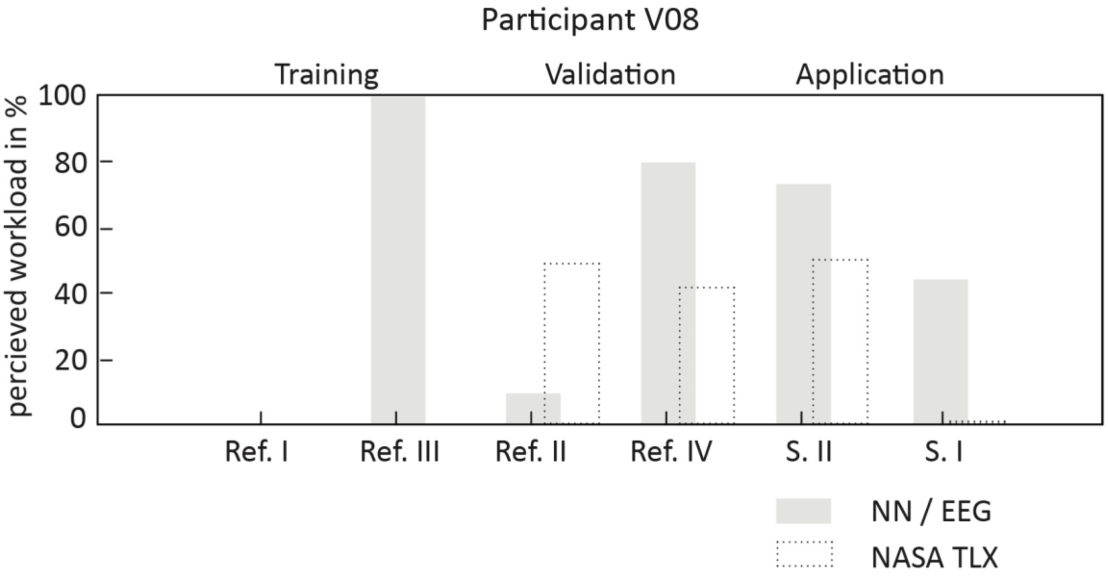
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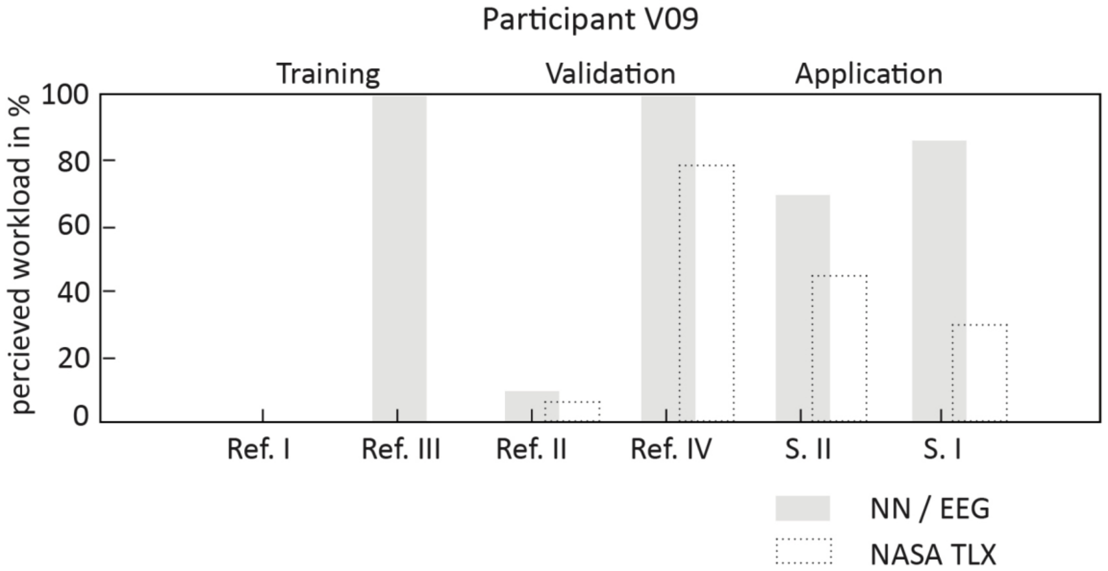
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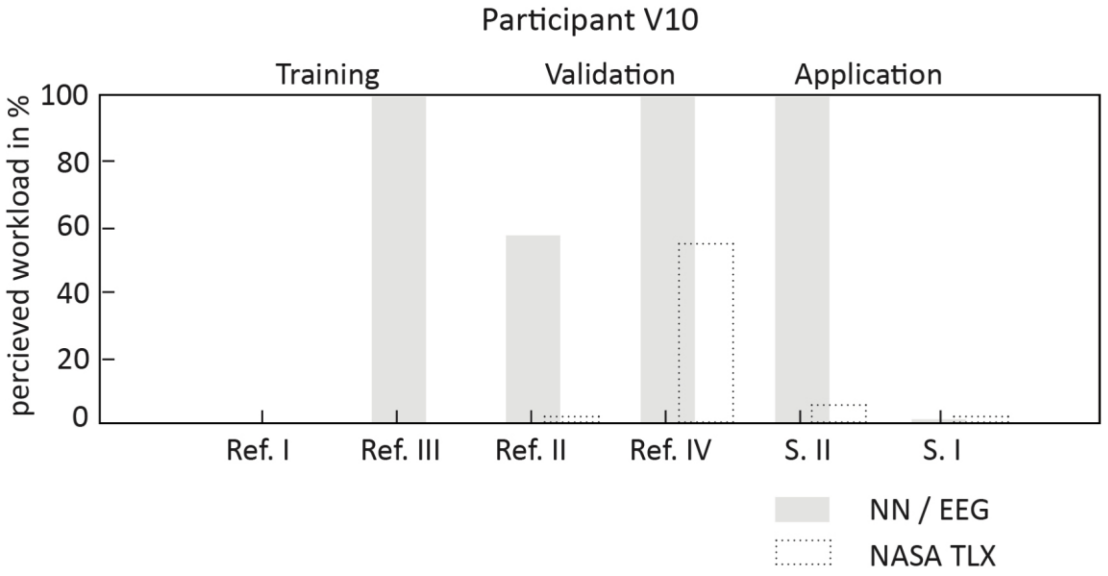
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