ACE Factories

humAn CEntred Factories

Human-centred factories from theory to industrial practice. Lessons learned and recommendations.

For industry practitioners and decision makers at local, regional, national and EU levels

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White paper on Human-centred factories from theory to industrial practice. Lessons learned and recommendations

Table of Contents

List of Figures

List of Tables

List of abbreviations

Abbreviation	Explanation
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AR	Augmented Reality
CNC	Computer Numerical Control
EFFRA	European Factories of the Future Research Association
EU	European Union
FoF	Factories of the Future
FOV	Field of View
GDPR	EU General Data Protection Regulation
H2020	Horizon 2020 - EU Research and Innovation programme
HMD	Head Mounted Display
HMI	Human Machine Interface
HRC	Human Robot Collaboration
IoT	Internet of Things
MR	Mixed Reality
OECD	Organization for Economic Cooperation and Development
ROI	Return on Investment
SME	Small or Medium-size Enterprise
VR	Virtual Reality

Executive summary

With the advent of the fourth industrial revolution called Industry 4.0, the industrial world has shifted further towards automation, where advanced workplaces are replacing existing working stations. Moreover, human-machine collaboration has taken a big leap forward, placing human operators in the centre of attention. As such, this paper forms a review of the lessons learned from the point of view of five EU funded H2020 research projects (A4BLUE, Factory2Fit, INCLUSIVE, HUMAN and MANUWORK, 2016-2020), working in parallel and constituting the Human-Centred Factories (ACE Factories) cluster. Knowledge and technology providers, as well as industrial partners, have grouped together to deliver solutions that will bridge the gap to the factories of the future. The purpose of this white paper is to share the ACE Factories cluster understanding of future human-centred factories and to provide recommendations on how to get this vision into industrial practice. This is a key report of the ACE Factories cluster, which aims to support the replication of successful innovative technologies tested through the end-users of the ACE Factories cluster projects. The core target groups of this report are people in academia, industry practitioners and policy makers at the local, national and EU levels.

The ACE Factories cluster considers five types of factory operators: the augmented and virtual operator, the social and collaborative operator, the super-strong operator, the one-of-a-kind operator, and the healthy and happy operator. Several technologies have been proposed and developed to support these types of operators. The evaluation of these concepts and technologies in ACE industrial cases has provided strong evidence on their benefits on industrial practice. Based on practical and scientific evidence, the ACE Factories cluster has identified several lessons learned and recommendations for successful technology and best practices adoption.

- Future factory operators can utilise augmented and virtual reality-based tools to get hands-on guidance on assembly, for training in factory operations and to support participatory workplace design. AR and VR are efficient tools for training on the job, which increases the productivity and the workers' well-being.
- Making operators' tacit knowledge, such as best work practices and problem solving, visible and accessible with social media-based tools can effectively complement the guidance provided by official documentation and formal practices.
- The know-how of industrial workers must be protected from unauthorized use especially by data and analytics companies.
- The usage of wearable apparatus like exoskeleton devices has shown their potential to reduce operator's physical fatigue, increase their overall safety and productivity.
- ACE pilot cases have shown that human-centred factory solutions have positive impacts both on operator wellbeing and productivity.
- The human-centred paradigm shift will only be successful if work processes are reshaped and new training approaches are introduced to support continuous development of skills taking into account personal capabilities, skills and situational preferences of individual operators.

➢ New technical solutions for the real-time measurement of operator's capacities/mental strain and automatic work adaptation may improve productivity and worker wellbeing.
➢ New technical solutions for real-time measurement of operator's physical strain and automatic adaptation of level of physical support may improve productivity and operator's safety.
➢ Ethically sound adaptation solutions support the aim of a sustainable and responsible industry.
➢ Providing factory workers ways to influence and improve their work will increase work motivation and productivity.
➢ Changing work roles should be implemented with consideration of the needs of elderly workers - no one is left behind.
➢ New work roles in manufacturing industry should be promoted to young people and those of differing abilities.
➢ Criteria related to trust in the human-robot collaboration (HRC) should be unavoidably considered.
➢ SMEs should be supported in adopting human-centred factory solutions.

1 Introduction

With the advent of Industry 4.0, the modern manufacturing world has shifted its focus to further increasing automation. Advanced workplaces are replacing existing stations. Moreover, human-machine collaboration has taken a leap, placing human operators in the centre of attention. As such, this white paper forms a review of the lessons learned from the point of view of five EU funded research projects (2016-2020) - A4BLUE, Factory2Fit, HUMAN, INCLUSIVE, and MANUWORK - working in parallel and constituting the [HumAn CEntred (ACE) Factories Cluster](ace-factories.eu) (ace-factories.eu). Knowledge and technology providers, as well as industrial partners, have grouped together to deliver solutions that will bridge the gap to the factories of the future. The ACE Factories cluster is a networking Cluster of five Factories of the Future (FoF) projects funded under the European Union's Horizon 2020 research and innovation programme. These projects are developing solutions for manufacturing work environments that adapt to each individual worker. Based on the common goals they are working towards, the cluster is a forum for sharing the projects' knowledge, progress, and results.

In the past, people were expected to adapt to machine requirements. Now, automation systems are being designed and developed so that they can recognise the users, remember their capabilities, skills and preferences, and adapt accordingly. Humans and automation are therefore taking advantage of each other's strengths, having a symbiotic relationship for enhancing the capabilities, skills and quality of their work. The result is more flexible, inclusive and safe workplaces, as well as better work conditions and increased productivity and improved quality. But, above all, this means increased worker satisfaction and work well-being, more empowered and engaged workers and increased interest towards factory work as a career, attracting young talented people.

The purpose of this white paper is to share the ACE Factories cluster understanding of future human-centred factories and to provide recommendations on how to get this vision into industrial practice. The white paper is structured as follows: In Chapter 2, the vision for human-centred factories of the future is presented. The chapter describes the ACE Factories cluster's shared Operator 4.0 vision of future factory work and related human-centred tools. Chapter 3 describes state-of-the-art methods and enabling technologies that can be utilised in order to implement the vision for future human-centred factories. Chapter 4 provides insight and lessons learned of applying the technologies described in chapter 3 upon several ACE Factories cluster projects' industrial pilot cases. The challenges, solution and impact of industrial pilot cases are described. In Chapter 5, recommendations are proposed, regarding methods and technology adoption and integration in human-centred factories. The recommendations target mainly industry representatives, people in academia personnel as well as policy makers.

2 A vision for human-centred factories

The fourth industrial revolution, often referred to as Industry 4.0, is already on its way. Enabled by advanced digitalisation, industrial internet and smart technologies such as Internet of Things (IoT), it is expected that Industry 4.0 will result e.g. in shorter development periods, individualisation in demand for the customers, flexibility, decentralisation and resource efficiency (Lasi, Fettke, Kemper, Feld & Hoffmann, 2014; MacDougall, 2014). Industry 4.0 will radically change many work roles in industry. There will be significantly greater demands on all members of the workforce, in terms of managing complexity, abstraction and problem-solving (Kagermann, Wahlster & Helbig, 2013). For the industrial workers, the revolution is expected to provide opportunities by the qualitative enrichment of their work: a more interesting working environment, greater autonomy and opportunities for self-development (MacDougall, 2014). The change in the factory floor work has been characterised as Operator 4.0 (Romero, Stahre et al., 2016). Future factory workers are likely to act much more on their own initiative, to possess excellent communication skills and to organise their personal workflow; i.e. in future industrial environments, they are expected to act as strategic decision-makers and flexible problem-solvers (ElMaraghy, 2005; Gorecky, Schmitt, Loskyll & Zühlke, 2014).

Future factory work will be qualitatively enriched and flexible and will require new qualifications to master the digital technology invading factories. Future factories should support current workers in learning new skills while tempting new workers who are already familiar with digital solutions. The Operator 4.0 paradigm shift cannot succeed just by introducing new technologies to the factory floor. The personal capabilities, skills and situational preferences of individual operators should be taken into account. Operators should be supported in taking responsibility for their competence development, and they should receive motivating feedback on their work achievements. Work processes need to be reshaped and new approaches to training are needed in order to support continuous development of skills. The operators should have possibilities to participate in designing their own work.

2.1 ACE Factories' Operator 4.0 vision

Societal and demographic changes are transforming the composition of the workforce. On the one hand there is an increment in the number of older workers who bring a long-time experience from which younger colleagues and companies can benefit but can suffer from physical decrements (e.g. visual and hearing acuity or selective attention). On the other hand, the number of *young* employees is in decline, particularly in the manufacturing sector due to younger people's preference to work in other kinds of jobs. This will yield a limited access to qualified employees. As a consequence, it becomes fundamental to make the best use of the entire available workforce, shifting to a more human centric approach.

An ageing workforce can be supported by modern technology to interact effectively with increasingly sophisticated and complex industrial machinery since their experience is crucial for successful and competitive production. In addition, incorporating new digital technologies (e.g. augmented reality) and using industrial social networks may help attract younger workers. Apart from paying attention to the older and younger workers, working systems must be more inclusive and adaptive to accommodate the special needs of workers with *disabilities* and enable them to work as efficiently as other workers (Kildal, et. al. 2018, Kildal, et. al. 2019). Consequently, disabilities must be treated as skills and therefore must be assessed in order to provide a set of instructions to disabled technicians that will enable them to be productive and thus positively affect their confidence.

A central component of Industry 4.0 is its human-centricity, described as development towards the Operator 4.0 concept (Romero, Bernus et al., 2016). Operator 4.0 refers to smart and skilled operators of the future, who will be assisted by automated systems providing a sustainable relief of physical and mental stress and allowing the operators to utilise and develop their creative, innovative and improvisational skills, without compromising production objectives (Romero, Bernus et al., 2016). Romero, Stahre, et al. (2016) postulated an Operator 4.0 typology and argued that one operator could incorporate one or several of the proposed types. The authors differentiated between the Super-strength Operator (e.g., using Exoskeletons), the Augmented Operator (e.g., using augmented reality tools), the Virtual Operator (e.g., using a virtual factory), the Healthy Operator (e.g. using wearable devices to track well-being), the Smarter Operator (e.g., using agent or artificial intelligence for planning activities), the Collaborative Operator (e.g., interacting with CoBots), the Social Operator (e.g., sharing knowledge using a social network) and the Analytical Operator (e.g., using Big Data analytics). New technical enablers such as virtual and augmented reality, robotics and wearables provide promising possibilities to realise the Operator 4.0 concepts.

The factory floor solutions addressed by the five projects that make up the ACE Factories cluster reinforce the concepts introduced by the original Operator 4.0 topology by Romero et al. (2016). Figure 1 illustrates the ACE Factories cluster Operator 4.0 concepts. The Super-strong as well as the Augmented and virtual operator illustrate how new technologies empower operators with new capabilities and enhanced sensing. The Social and collaborative operator illustrates how operators and the whole work community can be engaged to influence on the work environment and work practices. The one-of-a-kind operator illustrates how manufacturing environments can empower workers by adapting to the different characteristics, skills and preferences of workers. The Healthy and happy operator emphasises that all the Industry 4.0 solutions should have positive impact on operator wellbeing.

Figure 1: ACE Operator 4.0 Topology (modified from Romero, Stahre et al (2016)).

Table 1 describes the original Operator 4.0 concepts and how the ACE Factories cluster solutions represent and widen them. Even if Smarter and Analytical operator concepts were not dealt within the ACE Factories cluster projects, these concepts are important when developing artificial intelligence-based operator support solutions. The "One-of-a-kind operator" has been added to the original topology, as in all the solutions, adaptivity has to be included to support the characteristics and preferences of individual workers.

Operator 4.0	ACE Factories cluster match
Augmented Operator	Augmented and virtual operator
Virtual Operator	
Collaborative Operator	Social and collaborative operator
Social Operator	
Super-strength Operator	Super-strong operator
Healthy Operator	Healthy and happy operator
Smarter Operator	---
Analytical Operator	---
---	One-of-a-kind operator

Table 1: Operator 4.0 and ACE Factories cluster operators match

Augmented and Virtual reality can support many operator tasks. Augmented reality (AR) tools are promising both for knowledge sharing and for training. There is a lot of research on AR instructions in industrial work. Earlier research has found that compared to paper-based instructions and training material, AR-based solutions are much faster to use, less errors are made and the operators appear to accept the technology (e.g., Baird & Barfield, 1999; Henderson & Feiner, 2011; Re & Bordegoni, 2014). The combination of simulation and virtual factory models brings a large number of proven advantages such as deeper understanding of the whole factory, and reduces commissioning ramp-up times and testing of proposed changes (Turner, Hutabarat, Oyekan & Tiwari, 2016; Mourtzis & Doukas, 2014, Segura et. al. 2018, Simões et al. 2019, Michalos et. Al. 2018).

The Social and collaborative operator concept includes, on the one hand, solutions to support participatory design and knowledge sharing and, on the other hand, human-robots collaboration solutions. Participatory design has been used actively since the 1980s to involve workers in the design of their own work and work tools (Muller & Kuhn, 1993, Seim & Broberg, 2010). Virtual Reality technologies are valid tools to support participatory design, because they support common understanding and collaboration among designers and users (Bruno & Muzzupappa, 2010). Knowledge sharing and communication are key aspects in the industrial work context. To improve team performance, organisations must ensure that knowledge is both shared and applied (Choi et al., 2010). Aromaa, Aaltonen, Kaasinen, Elo and Parkkinen (2016) presented a study in which Augmented Reality applications were successfully used in knowledge sharing between industrial maintenance technicians. Augmented Reality is a promising tool for knowledge sharing as it connects information to the physical context. Regarding collaborative robots, the main goal is to join the flexibility and dexterity of humans and the strength and repeatability in semi-structured environments while safety is guaranteed in them.

The Super-strong operator concept involves the usage of wearable apparatus, such as exoskeleton devices, that have the potential to reduce the operator's physical fatigue, increase their strength, overall safety and productivity. Exoskeleton devices have been successfully used for non-industry related applications, such as rehabilitation of physically weak, injured or disabled people and for military purposes aiding soldiers carry heavy loads (Karvouniari, Michalos, Dimitropoulos & Makris, 2018). Attempts to introduce exoskeleton devices in industrial environments have been made, in applications where operators had to work standing up continuously (Spada, Shibaudo, Carnazzo, Di Pardo, Chander, Gastaldi & Cavatorta, 2018).

The Healthy and happy operator concept can be supported by solutions that monitor physical and mental fatigue, and solutions that give the worker motivating feedback. While many traditional ergonomics and physical safety challenges disappear when operator work becomes knowledge based, new challenges related to cognitive ergonomics may arise as a result of higher mental workload. New technical enablers such as virtual and augmented reality devices and exoskeletons may, therefore, raise new ergonomics and safety concerns. Work environments should be designed to enhance both productivity and work well-being, as these factors are interconnected (Edwards & Jensen, 2014). Designing for well-being requires focusing both on job satisfaction and work engagement (Schaufeli and Bakker, 2010).

The one of a kind operator concept promotes that each operator's individual differences should be considered when putting together humans and automation to take advantage of each other's strengths to balance flexibility and productivity requirements in an easy and cost-effective way. To respond to this challenge, companies need to re-design production systems and implement an adaptive strategy to increase adaptability, lower efforts for setting up and executing operations, compensate workers' limitations, and increase workforce satisfaction to improve levels of organisational commitment and retention. In earlier research adaptation according to the human operator has been developed from different viewpoints: adaptation to human physics with work ergonomics (Heilala & Voho, 1997), adaptation to human skills (Heilala & Voho, 1997), adaptation of interaction (Rothrock, Koubek, Fuchs, Haas & Salvendy, 2002) and adaptation of the Level of Automation (LoA) (Johansson et al. 2009).

One of the key components of adaptive production is resource scheduling (Leung, 2004). Scheduling refers to the organisation of production with different available machines, different employees, whose efforts should be coordinated towards reaching common goals. Worker preference-based task assignment and scheduling algorithms, also considering skills and capabilities, support the adaptability of the scheduling process (Jaturanonda & Nanthavanij, 2011; Colucci et al., 2004).

3 Methods and enabling technologies for future operators

This chapter presents the different aspects that characterise each of the operators proposed by the ACE Factories cluster. The aspects presented here have been worked on within the five projects that represent the cluster. This is by no means to say that they are the only ones that depict these operators.

The following table shows the relationship between such aspects and operators.

Operators envisioned by the ACE Factories cluster	Aspects dealt with within the cluster projects
Augmented and virtual operator	- Off-the-job and on-the-job training and guidance - Co-design
Social and collaborative operator	- Industrial social networking and knowledge sharing - Human - robot collaboration (HRC)
Super-strong operator	- Exoskeletons
One-of-a-kind operator	- The adapted workplace - Load balancing
Healthy and happy operator	- Empowering feedback on work well-being and work achievements - Worker satisfaction assessment

Table 2: ACE Factories cluster types of operators and the aspects that characterize them within ACE Factories cluster

3.1 Augmented and virtual operator

Off-the-job and on-the-job training and guidance

Workers must undertake regular training to acquire and refresh the skills that are required due to new procedures. Providing adaptive tools that deal with human variability for training purposes will facilitate the learning process. Mixed Reality (MR) technologies allow the adaptability of training and guidance to changing circumstances (e.g. new devices, new procedures, new workers, workers with different skills, etc.).

On the one hand, Virtual Reality (VR) may be used to support off-the-job training by recreating complete virtual environments in which the trainee would be introduced to the new tasks by performing them over virtual equipment, as developed in the INCLUSIVE, MANUWORK and HUMAN projects. In such virtual environments, workers can practice working with the manufacturing systems well before those systems have been installed on the factory floor. In a virtual environment even exceptional situations such as solving error situations can be practiced safely. Furthermore, a virtual environment allows for a wide range of personalisation to the needs of the worker and the procedure that is being trained. Therefore, the requirements of vulnerable user groups, such as ageing or disabled operators, can be addressed.

On the other hand, Augmented Reality (AR) supports on-the-job guidance by creating mixed environments in which real components (e.g. automation mechanisms, tools, parts) are augmented with virtual elements designed to reduce workers' cognitive load and increase their productivity. New AR systems not only deliver algorithms to robustly augment physical objects in adverse conditions, but also tailor the information that they convey to workers based on their capabilities, skill level and personal learning targets. Such systems provide workers with information that can be unequivocally understood in fluctuating degrees of worker attention, which is one of the best strategies to reduce errors and accident risk. Also, this unlocks possibilities to use non-trained workers for specific jobs/tasks and to overcome the limitations of needing access to specialised labour workforces.

With step-by-step AR guidance workers can manage tasks they are not trained for (i.e. learning by doing), as introduced in the A4BLUE, FactoryFit, HUMAN and MANUWORK projects. The steps required to carry out every task are displayed in a non-disturbing way to promote usability without distracting the workers from the actual procedure. Combined with remote assistance support, AR can deliver real-time hands-free guidance to workers with content depicted directly within their field of view, therefore reducing the time needed to access information.

Co-design

In the factories of the future, the collaboration of different actors is promoted to engage the work community in co-design activities. Factory2Fit's platform supports seeing one's own job, other workers' jobs and their roles in the overall context of the manufacturing process. Co-design with a virtual factory was extremely well accepted when Factory2Fit concepts were introduced to shop stewards of different factories (Kaasinen et al., 2019). The workers thought that the virtual factory provides a platform that facilitates making their proposals visible and supports sharing ideas between different stakeholders.

The HUMAN project's approach particularly focuses on providing the tools necessary for evaluation and co-design of workplaces. Their solution promotes the collaboration of two actors, namely the workplace engineer and the operator. It utilises Virtual as well as Augmented Reality in order to provide the engineer with all of the tools they need to simulate real manufacturing environments and processes, access them, modify the virtual workplace and check for the effectiveness of the modifications in terms of ergonomics, usability and efficiency. The solution has two main modes; the simulation mode where the operator may perform the task in an immersive virtual shop floor, and the design mode where both actors are able to visualise and alter the layout of the workplace in a collaborative way. It also provides the engineer with all of the necessary tools to be able to analyse the ergonomics, usability and efficiency of manufacturing environments, and check improvements after the workplace redesign.

3.2 The social and collaborative operator

Industrial social networking and knowledge sharing

The importance of a highly-collaborative, knowledge-intensive, service-oriented and efficient manufacturing industry is emerging as a new promising business paradigm, as well as an integrated technical approach for dynamic collaborative manufacturing networks.

Organisations want a unified observational point to discover, design and share better work practices. They want to simplify support and cut costs by providing employees with easy-to-use self-help and peer-based assistance: a place where users can quickly get the answers and information without having to call a help desk, saving precious staff time.

Moreover, they also want to inspire, develop and retain the best talent by upskilling and motivating staff to improve the quality and relevance of skills formation, and making skills and qualifications more visible, comparable and easily reachable.

Workers possess a lot of tacit knowledge regarding good work practices and problem solving. Making this knowledge visible and accessible with social media-based tools will complement the guidance provided by official guidance and documentation. Connecting the knowledge to the manufacturing environment context, so that workers have access to situationally relevant information in a situationally relevant form, will further facilitate the sharing and accessing of knowledge such as good practices, notices and observations.

The experiences from the Factory2Fit project show that workers have seen different approaches that have aimed to support knowledge sharing at work. Often those solutions have not succeeded in motivating workers to share knowledge. It is important to base knowledge sharing on actual worker communities, because communities cannot be initiated simply by introducing a knowledge sharing tool. Added value can be gained by integrating the knowledge sharing to the manufacturing environment, so that knowledge is connected to physical objects or actual situations on the factory floor (Aromaa et al., 2019).

Similarly, A4BLUE's Collaborative Knowledge Platform intends to drive engagement and higher employee productivity: by encouraging employees to leverage collective knowledge and immediately apply it to their everyday work; by offering access to several collaboration tools; by providing easy access to the people who will put the right skills and knowledge at employees' fingertips; by transforming old ways of working and communicating to a new way of digital collaboration, contribution to innovation and real time feedback, accessible at anytime from anywhere, and perfectly integrated with the rest of the A4BLUE Adaptive Framework.

On the other hand, the MANUWORK Industrial Social Network tool (aka RAPpID), places the worker and his/her co-workers in the centre, focusing on quick and user-friendly access to data and information related to their workplace. This allows organisations to reduce waiting/downtimes, increase overall efficiency and utilise accumulated knowledge.

Human - robot collaboration (HRC)

Future factory workplaces are bringing humans and robots together, where both partners share work on a single task, collaborating and complementing each other in the different productive tasks, and combining workers' dexterity, flexibility and problem-solving skills with robots' repetitiveness, speed and precision. Although these new working methods will bring numerous benefits, their transformation of manual work roles means new emergent human-centred considerations are needed.

The European Factories of the Future Research Association (EFFRA) already mentions safety, ergonomics, adaptability and acceptance in the document *Factories 4.0 and Beyond* (EFFRA 2016). Safety is the main key factor, which must be guaranteed 100%, and this has always been a fundamental part of industrial robot system design and integration. However, safety from physical harm is not the only important issue because closer and more collaborative human-robot integration brings a number of psychological and emotional impacts as well. For this reason, Human Factors are becoming increasingly relevant. User experience needs to be optimised as it is a key determinant of acceptance and, therefore, of the human-robot system performance. It is no longer enough to ensure that a system is safe, but that workers will trust that it is safe without the fences and physical safeguards that have traditionally kept them segregated and safe. Workers will now need to feel safe and comfortable without these physical barriers, so achieving the right level of trust is crucial: if it is too low, workers will not be able to perform tasks effectively, but if it is too high, they may become too complacent and careless in the collaboration. For this reason, the A4BLUE project included measures of trust across all of its participant studies using a bespoke scale especially developed for the context of collaboration with industrial robots.

Supporting human-robot collaboration requires understanding the requirements of HRC as well as the differences to existing approaches where the goal is more automation, such as in the case of self-driving cars. In the MANUWORK project, a framework called 'levels of collaboration' has been proposed to support this and posit that this framework supports a mental model conducive to the design of lines incorporating HRC. To design an HRC scheme in a human-robot collaborative cell, it is essential that the human worker's profile (his/her skills and capabilities) are taken as the starting point (including any disabilities and age related factors). Then, an interaction cycle is designed in which automation technologies bring in the additional skills and capacities to carry out production tasks collaboratively at the quality and productivity levels that are required.

A4BLUE is also contributing to these collaborative environments by implementing different features. In terms of safety, this is covered with the incorporation of sensors to monitor the coexistence area with capabilities of identifying inanimate obstacles and humans so that the robot's behaviour is adapted to guarantee safety (e.g. robot speed). Moreover, the robot's adaptation goes beyond this and can consider each worker's profile (e.g. their anthropometric characteristics, skills, preferences) when accomplishing productive tasks in collaboration.

New ways of communication between humans and robots are also enhanced where usual means are complemented with voice and gesture interaction mechanisms so that the system can further support different workers' capabilities or preferences. Usability and worker satisfaction tests during implementation phases guarantee correct adoption of such features and sustainability of solutions through time.

3.3 The super-strong operator

Exoskeletons

While some technologies mentioned above will improve the workplace by mentally supporting operators during the execution of everyday tasks, another aspect to consider is how to provide physical support. Physical work demands may be assisted by the introduction of collaborative robots, as already described. However, not all tasks can be automated yet. Some manual tasks require repetitive movements in non-ergonomic positions, such as the lifting of a box or drilling with hands positioned above the shoulders. The HUMAN project proposes solutions based on exoskeletons to support workers in such activities.

For cases that involve, for instance, tasks with the operator's arms positioned above their shoulders, such as drilling, clamping, and riveting a high number of screws per shift in the assembly of an aircraft, an upper limb exoskeleton is used. These operations are performed repetitively on different aircraft parts (e.g. the fuselage, the wings and the tail) requiring workers to keep their arms elevated for prolonged times, often while holding tools. The exoskeleton provides assistance to the upper limbs by helping operators to maintain elevated arms and reducing the effort that is required of the shoulder muscles in this position. The exoskeleton was conceived as quasi-passive, in order to be simultaneously lightweight and allow users to set different levels of assistance.

Cases involving the lifting of heavy boxes to transfer them to pallets, where the action is repeated numerous times throughout a shift, may lead to pain in the pelvic area. Thus, the pelvic exoskeleton solution developed within the HUMAN project supports the operator's back, reducing muscle strain to this area. It is an active and compact solution which involves control algorithms and assistive strategies.

3.4 One-of-a-kind operator

The adapted workplace

Human-centred factories should accommodate the needs of workers with different skills, capabilities and preferences. Adaptive human-automation interaction solutions improve the flow of working and support the worker in understanding and developing his/her competences. The main principle is that the worker is an expert at his/her own job and thus s/he should have an active role in its adaptation. That is why worker preferences should be taken into account in a worker model. The adaptation solutions in all ACE Factories cluster projects utilise the worker model to change the automation level and other system features accordingly.

An adaptive manufacturing system should provide operators with personalised and context aware assistance to sustain the execution of the task at hand in an efficient and effective manner. In addition, the system should cope with workers' own variability, in terms of evolving individual physical, sensorial and cognitive capabilities, characteristics, skills and preferences. For example, in A4BLUE a robot adapts to the anthropometric characteristics of workers while collaborating with them on assembly tasks, whilst the system also provides assistance to the worker through AR according to their level of competence and experience. The need for adaptivity is especially important when vulnerable users, such as those who are cognitively or physically impaired, elderly or less skilled, are involved. While the immediate goal of an adaptive system is to improve the performance of operators when interacting with the system, the ultimate goal is to enhance skills. As a consequence, adaptive systems become easy to use for all operators.

Adaptive systems dealing with personal data must fully consider issues related to data protection. The General Data Protection Regulation (GDPR) defines the basic principles for data protection. Principles and practices for data protection still need to be negotiated and agreed at the workplace. The Worker Profile Dashboard developed in Factory2Fit provides the worker with a tool to access his/her profile data and to define who can access the profile. INCLUSIVE has found a way to make the operators anonymous, assigning them a code and assigning the right profile to the code.

Load balancing

In real-life assembly, the existence of different sources of variation threatens assembly targets. One source of variability that has a significant impact on assembly performance is the variation in task time due to human or environmental factors such as workers' tiredness or lack of skills, complex operations, and machine breakdowns. MANUWORK introduces mathematical algorithms to solve the assembly line balancing problem for different kinds of line configurations (such as straight and U-shaped line designs).

3.5 The healthy and happy operator

Empowering feedback on work well-being and work achievements

In future factories, operators are empowered to take responsibility for their work well-being and competence development. This is supported by the quantified worker approach in the Factory2Fit project where monitoring of work activities and worker well-being is utilised to give the worker empowering feedback of his/her work well-being and work achievements (Heikkilä et al., 2018). The worker is also supported in seeing the link between his/her well-being and work achievements. This supports the worker in the continuous development of his/her competences.

Worker satisfaction assessment

Several studies support the assertion that worker satisfaction positively influences productivity. But how can we measure worker's satisfaction? Satisfaction is a multidimensional psychological concept with cognitive (evaluative), affective (or emotional), and behavioural components but it is not directly observable. Levels of satisfaction are the result of a collation of these dimensions in response to a variety of factors affecting a situation, but perceptions are largely subjective. It is therefore likely that they will vary from individual to individual depending on their inherent traits and previous experiences. Worker satisfaction is also subjective but influenced by aspects of the surrounding situation. It manifests itself in levels of motivation as the degree to which a person wants to work well will be an outcome of:

- Extrinsic factors: aspects of work in the environment and organisation that are external to work tasks (e.g. colleagues, pay or working conditions, etc.);

- Intrinsic factors: aspects of work that are directly related to the performance of work tasks (e.g. recognition, control, responsibility, etc.);

Although it is not possible to directly measure satisfaction, it is possible to identify and measure the observable factors that affect satisfaction. Research into satisfaction has developed models that depict this relationship and some incorporate work-related factors such as those mentioned above. However, the effect of specific types and characteristics of technology on user satisfaction is missing in such models.

Currently, there is no available model or tool for industry to use to optimise satisfaction in automated work system design, despite the ongoing significant rise in industrial automation and human-system interactions. A4BLUE has developed a new worker satisfaction model for the specific context of modern automated work systems, which is derived from empirical data gathered from real operators and participants across use case studies of key technologies. This new worker satisfaction model identifies the principal components of automation system design that need to be addressed to optimise human satisfaction, and it will enable development of psychometric measures that will bring a much-needed means of directly measuring satisfaction impacts. By identifying each factor that affects satisfaction it is possible to measure how satisfaction varies across the factors, and from individual to individual. This understanding enables the technology to be varied in such a way that maximum satisfaction is acquired for each operator.

In the INCLUSIVE project, when developing the model of Human Machine Interface (HMI) user satisfaction, it was assumed that some working environment factors can influence its assessment or are particularly important in the context of an inclusive industrial environment. These are physical factors, such as noise, temperature, dust or posture, as well as psychosocial working conditions, such as autonomy, participation, justice or social support. Therefore, in this 'Satisfaction with the adaptive HMI and working conditions' model two main components were included: 1) Satisfaction with working conditions (including both physical and psychosocial working conditions), 2) User satisfaction with the adaptive HMI (including satisfaction with health and safety). Based on this model and the usability concept, a questionnaire to measure worker satisfaction was developed in order to have an empirical confirmation of this model. In the first section of the questionnaire, the questions/items measuring working conditions were included, in particular abovementioned physical working conditions and psychosocial working conditions. In the second section of the questionnaire the questions/items measuring user satisfaction with the adaptive HMI were included: user satisfaction with safety, design/visibility of the interface, ease of use and system efficiency. As the adaptive HMI includes three modules (Measure, Adapt, Teach), level of satisfaction with these three modules is also measured in the questionnaire. Monitoring the physiological and psychological condition of workers in order to adapt the working systems (the Measure module) requires compliance with strict ethical rules. Therefore, questions on this subject were also included in the worker satisfaction questionnaire.

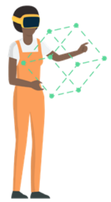
In MANUWORK, a state-of-the-art analysis of existing approaches for the description and evaluation of workers' satisfaction has been performed. More than 50 articles have been included in the survey, which has been continuously fed during the lifetime of the project.

The analysis showed that currently there are no instruments for measuring worker satisfaction, which can be directly applied to the MANUWORK use cases, mainly because of the lack of attention to automation and its relations to job satisfaction. Hence, MANUWORK has adapted existing standardised questionnaires evaluating job satisfaction, as well as questionnaires evaluating human robot-interaction and usability of technologies in order to propose instruments capable of evaluating the dimensions interesting for the MANUWORK industrial partners. The usability of the proposed questionnaires has also been evaluated and is tested in real workplace environments.

In turn, the Factory2Fit approach proposes extending the view from work satisfaction to work well-being in general. New Operator 4.0 work tools and related new work practices have the potential to enhance productivity and work well-being, but these positive impacts do not materialise automatically. How should the targeted impacts then guide the design process? It requires, at least, that the objective of the design is set accordingly and kept in focus throughout the design process. Operator 4.0 solutions should directly support the workers themselves and enhance their possibilities to influence their work. The challenge in designing such solutions is to find ways to guide the design so that the outcomes of worker well-being constantly and efficiently enhance the design. This cannot be obtained by just emphasising well-being in design as well-being is the result, not the means. In the design process, it is necessary to focus on immediate implications of the design decisions from all relevant perspectives such as usability, user experience and safety. The design decisions then have wider impacts on worker well-being, and those impacts should be foreseen in the design. The Factory2Fit project has introduced a design and evaluation framework that supports focusing both on immediate implications of the design and wider impacts on work well-being and productivity (Kaasinen et al., 2019). The framework has successfully supported the design, evaluation and impact assessment activities in developing Operator 4.0 solutions.

4 Lessons learned from the industrial use-cases

The following paragraphs are dedicated to the presentation of practical implementations for the solutions discussed in the previous chapters in the context of the future workers. Furthermore, the unique lessons learned from each use case are also discussed. Table 3 presents the aim as well as the contribution of each use case. As such, Table 3 is divided according to the five operator types discussed in the previous chapter. For each use case the contribution is reflected using 2 symbols, namely a full circle for a strong contribution, half full circle for moderate contribution, and an empty cell indicates minor or no contribution to the corresponding operator type.

Use cases	Project	 Augmented and virtual operator	 Social and collaborative operator	 Super-strong operator	 One-of-a-kind operator	 Healthy and happy operator
4.1 AIRBUS pilot case: Towards a next generation hydraulic system Automation and VR/AR	A4BLUE	●			◑	●
4.2 UTC pilot case: AR Assembly Guidance (ARAG) Solution - supporting workers in procedural tasks	Factory2Fit	●				◑
4.3 Prima Power pilot case: Hands-on pre-training in a virtual environment	Factory2Fit	●			◑	◑
4.4 COMAU use case: workplace optimization and operator mental support	HUMAN	●				●
4.5 PRIMA use case: AR training and support for bending operations	MANUWORK	●			◑	●
4.6 Lantegi use case: AR assisted assembly of electrical boards	MANUWORK	●				●
4.7 CESA use case: Assembly and auxiliary operation of the Main Landing Gear Retraction Actuator	A4BLUE	●	●		◑	●
4.8 RWTH lab use case: Assembly and auxiliary operation in automotive final assembly	A4BLUE	●	●		●	●
4.9 Continental pilot case: Co-design	Factory2Fit	●	●			

Use cases	Project	 Augmented and virtual operator	 Social and collaborative operator	 Super-strong operator	 One-of-a-kind operator	 Healthy and happy operator
4.10 Volvo use case: AR visualization of industrial simulation	MANUWORK	●	●			
4.11 UTC pilot case: On-the-job learning	Factory2Fit		●		◑	◑
4.12 Prima Power pilot case: Social Media Platform - engaging worker participation and knowledge sharing	Factory2Fit		●			◑
4.13 AIRBUS Defense & Space use case: short-term physical and mental support	HUMAN	●		●		●
4.14 ROYO use case: short term physical and mental support	HUMAN	●		●		●
4.15 IK4-TEKNIKER lab use case: Collaborative assembly of latch valve	A4BLUE	◑	●		●	●
4.16 Continental pilot case: Task Distribution Engine - Multi-criteria dynamic task prioritization and scheduling	Factory2Fit				●	◑
4.17 SCM use case: new HMI for woodworking machines	INCLUSIVE	◑			●	●

Use cases	Project	 Augmented and virtual operator	 Social and collaborative operator	 Super-strong operator	 One-of-a-kind operator	 Healthy and happy operator
4.18 SILVERLINE use case: introduction of a robotic cell in the production shop floor	INCLUSIVE	●	◗		●	◗
4.19 E80 use case use case: introduction of a robotic cell in the production shop floor	INCLUSIVE				●	◗
4.20 Prima Power pilot case: Worker feedback Dashboard - empowering feedback on work well-being and achievements	Factory2Fit				◗	●

Table 3: List of industrial use cases

4.1 AIRBUS pilot case: Towards a next generation hydraulic system Automation and VR/AR

Challenge: The assembly of a complex hydraulic system of the A350 Aircraft consists of several manual operations as well as big diversity of components. The challenge arising, is to provide assembly instructions adapted to the worker's profile and context. Moreover, accurate information must be traceable and available to quality inspectors.

Solution: The proposed solution comprises an adaptive smart tool and an AR instruction application using HoloLens wearable devices and a framework for ensuring digital continuity starting from the data recorded in the system for manufacturing engineering up to the execution and analysis phase (see video on https://vimeo.com/337518814).

Impact: The goals for this use case include assembly time reduction, minimization of errors, and increase of efficiency, productivity and quality. What is more, with AR training and learn-by-doing method adoption, productivity of newcomers is also increased. Finally, a full quality assurance approach and traceability for supervision is enabled.

Lessons Learned: Workers' opinion is key, especially for decision and acceptance, during the design and development of adaptive automation solutions.

Figure 2: Off-the-job training, and on-the-job guidance through XR technologies at AIRBUS

4.2 UTC pilot case: AR Assembly Guidance (ARAG) Solution - supporting workers in procedural tasks

Challenge: Manual assembly of large size industrial products is a complex task, accompanied by paper-based instruction manuals. As a result, using such static documentation increases the cognitive load of workers and requires frequent travelling between the assembly unit and the tool magazine.

Solution: The ARAG solution, replaces paper-based instructions with holograms, which are displayed to the technician's field of view (FOV) through a head-mounted display (HMD), overlaid on the real product. Further utilizing HMD's capabilities, user is free to interact and manipulate the 3D objects, by altering their position, pose and scaling.

Impact: ARAG solution reduces the cognitive load, and increases the technician's satisfaction, while the precise guidance assures optimality and correctness in task execution. Furthermore, with the proposed solution training time is minimized as well as inspection by experts, also reducing manufacturing times and maximizing resource utilization.

Lessons Learned: ARAG solution was piloted in a factory of United Technologies Corporation (UTC). The validation results reflected the potential of the solution, technicians' acceptability to solutions specifically designed for supporting them in complex operations. Recent studies have shown that gamification tools can be utilized in industrial AR solutions for reducing technicians' learning curve and increasing their cognition (Tsourma et al., 2019).

4.3 Prima Power pilot case: Hands-on pre-training in a virtual environment

Challenge: In highly automated metal processing lines, intense customer training is needed. On-site training is not sufficiently efficient; thus, a virtual training solution is needed.

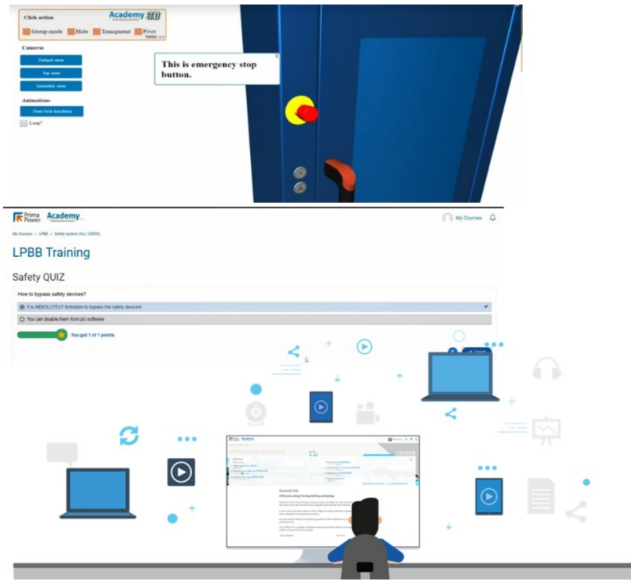


Figure 3: A view of the pre-training tool at Prima Power Pilot case

Solution: The proposed online training solution utilizes 3D models, videos and textual guidance to enable training technicians in realistic working scenarios. Each training task is followed by questions or learning exercises (quiz) for highlighting the most important matters of the topic.

Impact: With the proposed solution, online training can be scheduled optimally, shortening training time. Moreover, training supports understanding and dealing with exceptional situations such as disturbances in production. Increased productivity and job satisfaction are expected, lowering the threshold of operators to start using the manufacturing line independently.

Lessons Learned: The developed tool could be extended to become a part of a bigger communication platform, between the equipment provider and their customers, aiming at strengthening their relationship.

4.4 COMAU use case: workplace optimization and operator mental support

Challenge: the challenge arising in the COMAU use case is the development of a solution for the continuous improvement of the workplace ergonomics, in build to order assembly lines, characterized by high customization, low production rate and increased manual work.

Solution: To support the above challenges, two services of Human are developed, namely the Workplace Optimization Service (WOS) and the Knowledge In-Time (KIT) Service. WOS is a Virtual Reality service for workspace redesign evaluating people, systems and processes, results, and the overall culture of the workplace. The KIT is a HUMAN service that will trigger Augmented Reality interventions to deliver the required knowledge to the operator when they require it.

Impact: Thanks to the use of HUMAN technology, COMAU assembly lines are more flexible to the anthropometric, physical and cognitive needs of the workers, and hence to the cognitive and physical requirements of variable operations of variable orders. This will reduce the set-up and production times.

Lessons learned: Both WOS and KIT services have been evaluated at COMAU in real life applications, showing that WOS has been well accepted by both operators and engineers as a valuable tool for eliminating motion waste and improve workplace ergonomics in production lines. The evaluation of KIT showed that the developed solution helps to reduce cognitive load of operators, reduce faults and improve efficiency.

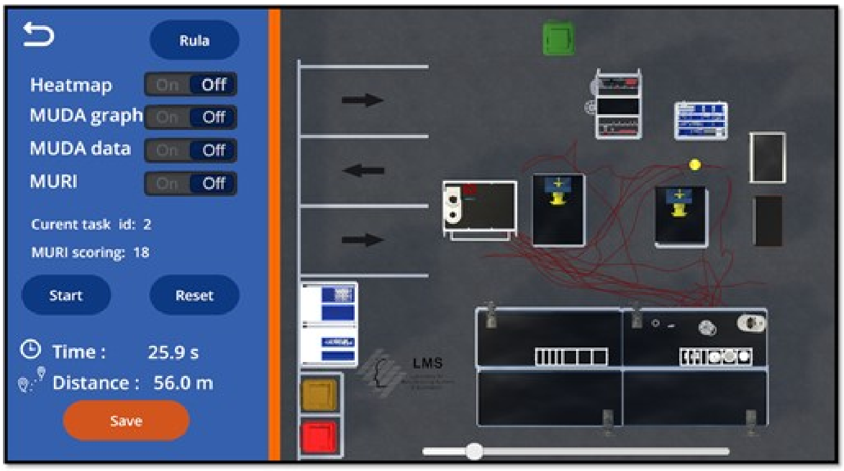


Figure 4: Workplace Optimization Service

4.5 PRIMA use case: AR training and support for bending operations

Challenge: Industrial processes, are often physically and mentally stressing for the machine operators, as they require handling and moving heavy objects and perform tasks which need advanced experience level. What is more handling and moving heavy objects around the workplace, includes health hazards. Equally, experience demanding tasks, require that machine operators are trained before taking action into the online production line. The challenges arising, include operators' satisfaction in their workplace, minimization of training phase, adaptivity of training to each operator's needs, minimization of physical and mental stress.

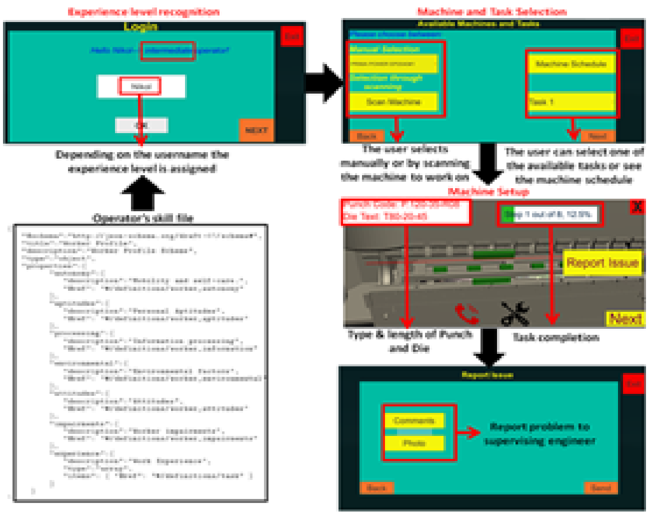


Figure 5: PRIMA use case of AR bending instructions adaptive to operator skills

Solution: An adaptive to worker's AR based solution has been developed, aiming at assisting press brake operators throughout the CNC machine operation and the tool setup phases, using an HMD.

Impact: Following the implementation of the developed framework, it is expected to increase machine operator's awareness, minimize errors, targeting at zero-defect manufacturing and minimize errors and task completion time.

Lessons Learned: The proposed solution has been piloted in a use case from PRIMA Power, which produces CNC press break machines. The validation of the solution reflected the increased awareness of the workers, their acceptability as well as a significant decrease in task completion time and errors during operation.

4.6 Lantegi use case: AR assisted assembly of electrical boards

Challenge: Taking into consideration the latest technological advances, and human-centric shift of manufacturing operations, people with disabilities must be kept in the loop and offer them the opportunity to become part of the production.

Solution: The solution developed comprises of an adaptive AR application for the training and assistance of technicians with disabilities in an assembly line, based on their skills assessment.

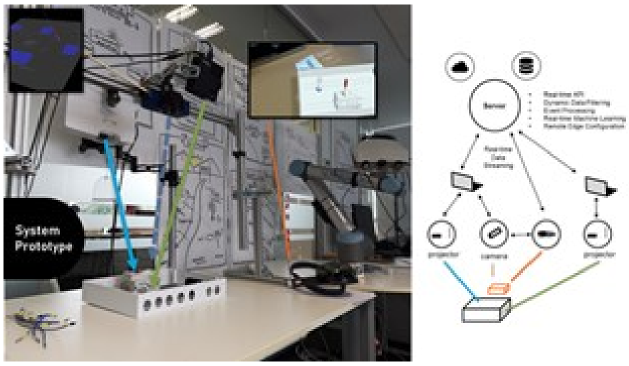


Figure 6: AR assembly guidance in the LANTEGI pilot case

Impact: Through this solution of MANUWORK, people with disabilities can be integrated in the production line of complex products.

Lessons Learned: With the provision of the right tools, every person can become part of a manufacturing system, including people with disabilities. These people are eager to work and feel productive which can affect global industry very positively.

4.7 CESA use case: Assembly and auxiliary operation of the Main Landing Gear Retraction Actuator

Challenges: CESA use case comprises the assembly of the retraction actuator for a commercial aircraft main landing gear. Two scenarios apply for this use case, i) an essential deburring operation, and ii) the assembly process itself. As such, challenges emerge from the lack of good ergonomics conditions and the need of wearing safety measures to avoid the related health issues. Moreover, there is a high variability in the deburring process, potentially causing quality issues and reducing productivity. On the contrary, assembly information is fragmented through different platforms, complex assembly instructions are not adapted to technicians' profiles, training is long and complex and feedback gathering mechanisms from technicians must be improved.

Solution: A collaborative robotic cell has been implemented for the deburring operation where the robot executes the most exhausting phases, while the worker focuses on final quality inspection. Regarding the assembly process, an AR solution, using ultra-real animations has been implemented to guide operators through tasks. Additional AR functionalities include the visualization of textual information (tips, best practices…), access to technical documents and voice recording (see video on https://vimeo.com/334929783)

Impact: In the deburring process, manual labor is reduced, resulting in improved ergonomic and safety conditions. Moreover, process variability is reduced while quality and productivity, increased. In the assembly process, training time has been reduced with the AR solution and access to centralized documentation is faster, with greater transparency and ease of use while its maintenance costs have been reduced.

Lessons Learned: The introduction of the is perceived by workers as helpful, especially when productive tasks are exhausting and may provoke health issues. They are not received with reluctance but as supportive in workers' tasks at the workplace. Regarding AR, it is generally considered as very useful, although the HMD (HoloLens) are too heavy for long time tasks.

Figure 7: Deburring robot and assembly operation at CESA

4.8 RWTH lab use case: Assembly and auxiliary operation in automotive final assembly

Challenges: The RWTH use case, is set in the ramp-up factory Aachen, for the assembly of a small electric vehicle prototype for short-distance traffic. This use case is challenging as technician's skills and experience are not considered, training times are high and due to the prototyping environment, the processes are complex and unknown to the workers. Moreover, special tools are often not where they are required. The movement for the trolley causes ergonomic issues and cognitive stress.

Solution: An AR based solution is proposed for instructions visualization enabling also on-job training activities and guidance. Regarding the ergonomics, an autonomous tool-trolley has been integrated including voice command and AR based gesture steering (see video on https://vimeo.com/361316515).

Impact: Improved technician satisfaction has been noted, as well as reduced process times and improved process efficiency with reduced errors. Moreover, the assembly process has benefited from better ergonomics and shorter waste time.

Lessons Learned: Adaptation within automation mechanisms is reported to be an enhancement at the workplace, according to workers.

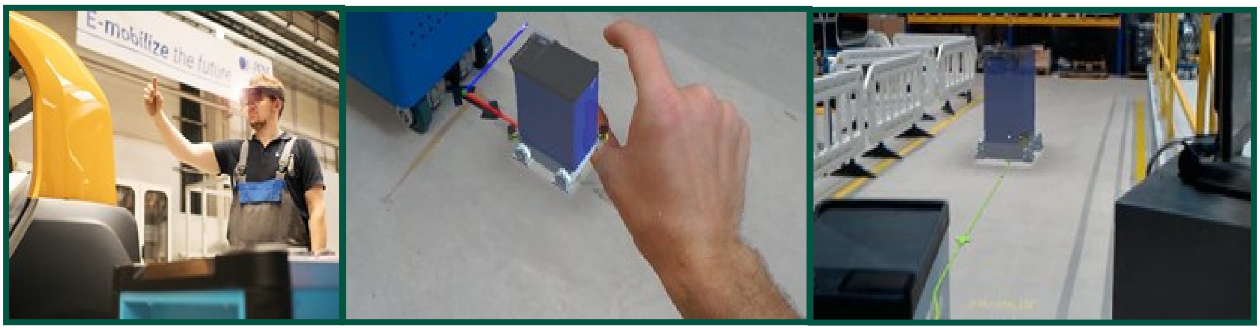


Figure 8: Augmented operator and interaction with an automated tool trolley at RWTH

4.9 Continental pilot use case: Co-design

Challenge: Due to the wide number of participatory design (PD) methods available today, correct method selection from a layman is challenging, as wrong method selection can lead to inadequate results and subsequently to reduced acceptance of PD (Bojko et al., 2019).

Solution: A software-based solution has been developed, simplifying the process of method selection. Based on user input, the algorithm determines/suggests the most suitable methods and hides the non-suitable ones.

Impacts: The method selection tool can also be used by non-experts as there is no need of vast know-how for the utilization of the offered tool. Therefore, the layman can easily select the right method out of a wide range. Codesign itself strengthens the companies as the workers can include their tacit knowledge into the workplace - or work process design and therefore have a higher commitment to their job once their ideas are implemented.

Lessons Learned: Within Factory2Fit there were 2 use cases for the codesign process piloted at Continental plant Limbach-Oberfrohna. One pilot was carried out for the workplace design and one for the work process design. An evaluation of the method selection and execution showed that there was good acceptance among the workers who contributed to the design process. To reach positive results during the codesign process it is essential to assess the boundary conditions and the group structure very well.

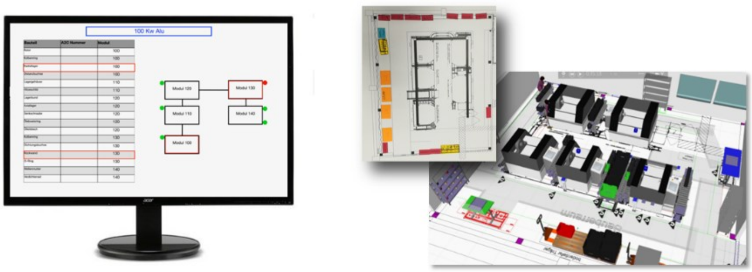


Figure 9: Co-design tools at Continental pilot case

4.10 Volvo use case: AR visualization of industrial simulation

Challenge: Industrial simulation can be very complex, making engineers' collaboration even more difficult. Furthermore, in large scale models, the perception of the actual model is not a one-man job. What is needed, is the development of a visualization tool for the simulation model in the user's physical environment aiming at better and quicker perception of the production line and its aspects. Additionally, user input must be taken into account, for making last-minute adjustments to the simulation model.

Figure 10: AR-based simulation tool for the VOLVO pilot case

Solution: IDSS-AR is an Augmented Reality visualization tool, supporting the simulation of assembly production line. The augmented model is interactable, so that users can reconfigure it and visualize effects in near real-time.

Impact: With the introduction of the IDSS-AR tool the user can walk around it and look view different aspects, elevating the perception of the simulation model, and enabling collaborative engineering.

Lessons Learned: The developed tool, has been applied in VOLVO, utilizing an offline production line, similar to the actual one. The perception time of the model has been reduced. Notably, more aspects of the model have been taken into consideration compared to the conventional simulation representation currently used. Finally, collaborative design of the simulation model has been rendered feasible, as a team of production managers can group and discuss on the same 3D model by making annotations.

4.11 UTC pilot case: On-the-job learning

Challenge: Manual assembly of highly customized large products requires skillful workers in varying levels. Henceforth, there is a need for a platform which renders expert knowledge on manufacturing operations available to anyone, anywhere, anytime efficiently enough to minimize waste of time and support upskilling novice technicians.

Solution: On-the-job learning is a web-based training tool allowing technicians have access to expert knowledge either on-line or off-line. A database containing videos of experts accomplishing relevant assembly tasks has been developed. Furthermore, the tool has been enhanced with an object detection algorithm, in order to retrieve the correct guidance video for the user.

Impact: With the proposed solution, access to expert knowledge is granted to anyone who is registered to the platform. What is more, supervisors are able to assign training courses to specific technicians for improving their skills.

Lessons Learned: On-the-job learning tool was piloted in a UTC factory producing air handling units. What is learned, is that in order to display the content more understandable, users must be able to interact with it, by viewing the components CAD files and make or read remarks.

4.12 Prima Power pilot case: Social Media Platform - engaging worker participation and knowledge sharing

Challenge: Resolving unexpected failures can be very challenging as manuals do not include every case. Tacit knowledge of experienced workers is a cornerstone in such situations. Thus, knowledge sharing and communication among technicians can provide a viable solution.

Solution: The Social Media Platform (SoMeP) is a web-based application, aiming to increase interaction, communication and knowledge sharing among technicians. SoMeP integrates discussions to the manufacturing environment and real-time alarms, thus giving easy access to situationally relevant knowledge. Gamification features aim at increasing motivation and participation in knowledge sharing.

Impact: SoMeP emphasizes in improving collaboration and communication between technicians and promotes knowledge sharing, and practices. In the long-term SoMeP can be used both as a communication channel and information exchange hub, but also as a valuable knowledge repository as well as an educational system.

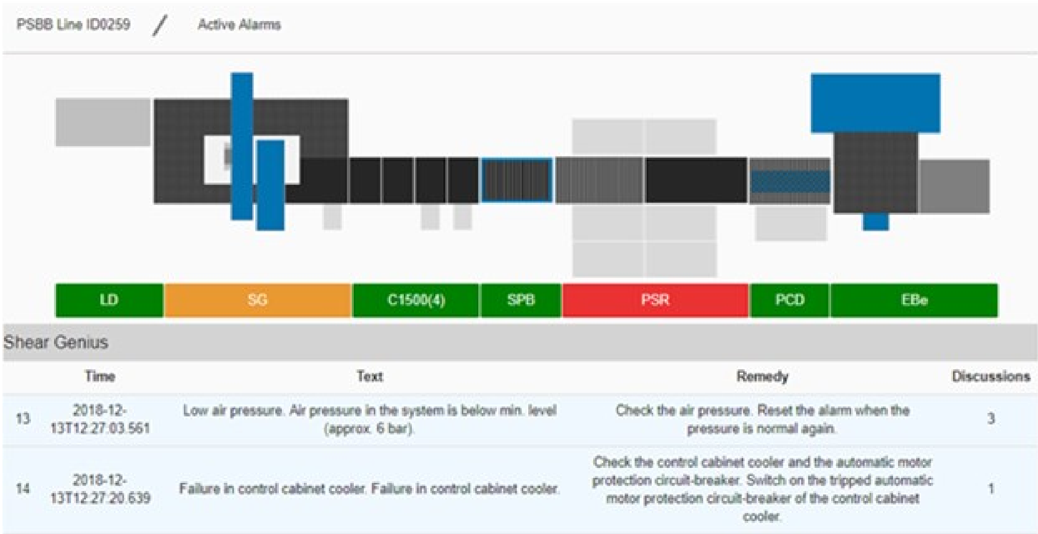


Figure 11: A view of the SoMeP at PRIMA Power pilot case showing production line, active alarms and relevant discussions

Lessons Learned: SoMeP was piloted at Prima Power, unveiling that the integration of production information and messaging is valuable and time-saving in getting guidance. Gamification can motivate workers to share knowledge (Zikos et al., 2019). The use of social media will require organizational policies e.g. in moderating the content (Aromaa et al., 2019).

4.13 AIRBUS Defense & Space use case: short-term physical and mental support

Challenge: The high level of product customization requires workers to adapt to continuously changing working conditions. In such assembly lines, operators have to execute a wide variety of complex tasks, continuously change tools and body position. Therefore, operators need to operate under physical and mental demanding conditions.

Solution: Two services were developed, the Exoskeleton service and the Knowledge In-Time (KIT) Service. This upper-limb passive exoskeleton with active regulations, is designed to deliver physical assistance to the operator during repetitive fatiguing tasks. The KIT service triggers Augmented Reality interventions to deliver knowledge to the operator when they require it.

Figure 12: Exoskeleton device tested in lab environment

Impact: As a result of the project, Airbus DS will be able to reduce the time to market of new aircraft and aircraft systems significantly, due to the important improvements in ergonomic and interactive workplaces, helping to increase the flexibility and pliability of the different production lines.

Lessons learned: Evaluation studies carried out at the premises of Airbus showed positive results for both of the Exoskeleton and KIT services developed for this specific use case. Both physical and mental fatigue of workers were reduced, as an outcome of the Exoskeleton and KIT services respectively. Workers were keen enough to adopt the new technologies to their everyday working activities.

4.14 ROYO use case: short term physical and mental support

Challenge: The use case of ROYO is concentrated in production lines, where employees are working with different automation machinery. Manual work takes place in the different workplaces all over the production lines. After the assembly, the products arrive to the palletization area where operators manually lift the boxes to palletize them and store them to the warehouse. Workers in that area are not aware if there has been a technical problem with a specific product and thus is expected to arrive later and are missing any information regarding the manufacturing order.

Solution: To support the above challenges, the Knowledge In-Time (KIT) service, the Exoskeleton service and the Operator Awareness and Support Tool (OAST), were developed. A lower limb passive exoskeleton is designed to assist the low back of operators performing lifting operations, specifically designed to support ROYO's palletization technicians. OAST provides cognitive support to operators, by creating awareness of the type of boxes arriving through the conveyors or for delays at previous production stages by real-time monitoring of the production line.

Impact: Through the solutions of HUMAN, it will be possible to process the production in smaller batches increasing the adaptability of each production line to all workers. Furthermore, HUMAN will enable ROYO to increase flexibility and adaptability in every production line at the shop floor, based on the ability to manage/predict their own effort during the shift avoiding pains beforehand, and moreover to eliminate waste and reduce errors and stress.

Lessons learned: KIT, Exoskeleton service and OAST have been evaluated at ROYO premises in real working conditions. KIT has been characterized as a valuable tool that reduces cognitive load and helps workers eliminate uncertainties at the assembly process. The combination of Exoskeleton service with OAST has helped to reduce the physical and mental stress of the operators at the palletization area of ROYO.

Figure 13: Operator Awareness and Support Tool

4.15 IK4-TEKNIKER lab use case: Collaborative assembly of latch valve

Challenges: The use case scenario involves the collaborative assembly of a latch valve in a fenceless environment including auxiliary activities as logistics and maintenance. Main challenges faced in this use case, are the adaptation of the workplace to process (e.g. work order, part reference, control program, etc.) and human (i.e. physical characteristics, capabilities, skills, etc.) and context (e.g. operation being performed) variability, the introduction multimodal Human-Robot interaction, the provision of adaptive assistance to the maintenance technician and the evaluation of trust, usability and worker satisfaction.

Solution: The assembly collaborative robot considers both the operation being performed and operator's anthropometric characteristics for control program selection and part positioning. Besides, the workplace includes multimodal interactions with both the dual arm assembly and logistic robots as well as with the Manufacturing Execution System. Verbal interaction includes natural speaking (i.e. Spanish language) and voice-based feedback messages, while nonverbal interaction is based on gesture commands considering both left and right-handed workers and multichannel notifications (e.g. push notifications, emails, etc.) (see video on https://vimeo.com/330958923).

Figure 14: Adaptation and interaction with collaborative robots at IK4-TEKNIKER

Furthermore, the maintenance technician is assisted by on event Intervention request alerts, maintenance decision support dashboard and AR/VR based step by step on the job guidance.

Figure 15: Assistance to maintenance technician at IK4-TEKNIKER

Impact: Adaptation to human variation is boosted, reducing work requirements and worker's physical demands without incrementing mental and cognitive workload. Additionally, safety and trust in collaborative workplaces are risen while improving usability and human satisfaction. Reconfigurability and flexibility are also improved, as well as efficiency due to the reduction of displacements.

Lessons Learned: Trust is identified as a key indicator in the pilot. Trust experiments are critical when introducing automation mechanisms that co-operate with workers.

4.16 Continental pilot case: Task Distribution Engine - Multi-criteria dynamic task prioritization and scheduling

Challenge: Due to the high number of tasks, the differentiation of requirements and the variety of machines, also amplified by the arrival of unexpected high priority tasks, there is an emerging challenge for automating production scheduling, using optimization methods.

Solution: Task Distribution Engine (TDE) is an application for task scheduling and assignment of human resources and machines, based on optimization methods. Supervisor is able to prioritize criteria for fine-tuning the automatically produced solution. The web-based interfaces for technicians aim at allowing them to update the status of their tasks, in order to update the supervisors and reconfigure the system. Two modes have been implemented, one for real-time operation and one for simulation. (Zikos et al., 2018)

Impact: TDE offers the generation of optimized production plans while the waiting time for the high-priority tasks has been reduced. Moreover, workplace is more user-friendly, and supervisors have a detailed overview of the running and planned work.

Lessons Learned: A use case derived from Continental's measurement lab has been used for validation, revealing the importance of task properties careful choice, time to familiarize employees to such system and assuring sensitive data security.

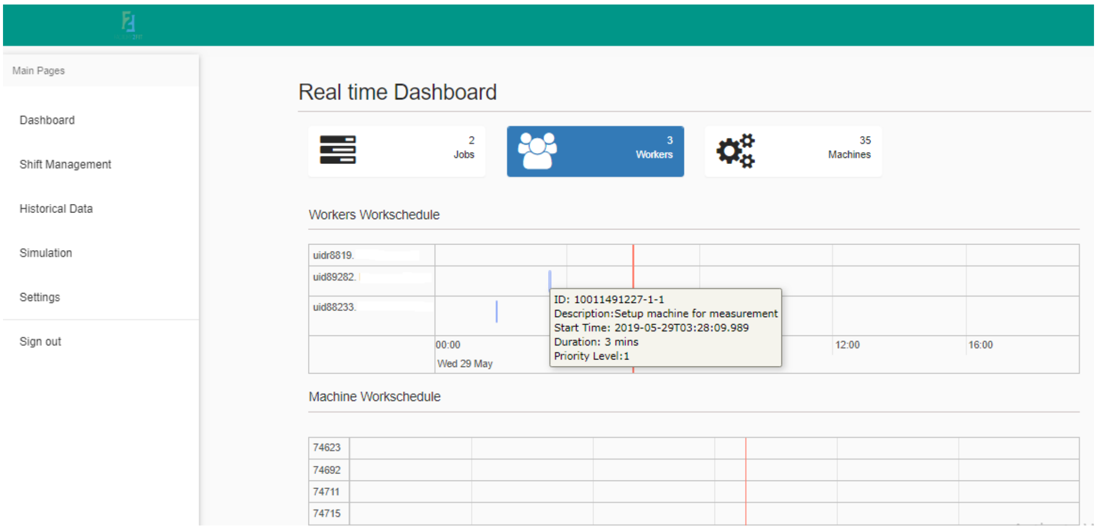


Figure 16: The Dashboard of the Task Distribution Engine user interface

4.17 SCM use case: new HMI for woodworking machines

Challenge: SCM group produces machining centers for the production of windows, doors, stairs, and solid wood parts, requiring heavy duty machining, while maintaining high precision and finishing quality. SCM customers are small artisan shops run by passionate but elderly people. This implies that, production scheduling is highly flexible and machine configuration needs to be changed very often and that operators using these machines typically have low computer skills.

Solution: An off-line training subsystem, providing a training environment based on a virtual simulation of the machine, was developed. This has been the SCM instantiation of the TEACH module of the INCLUSIVE framework.

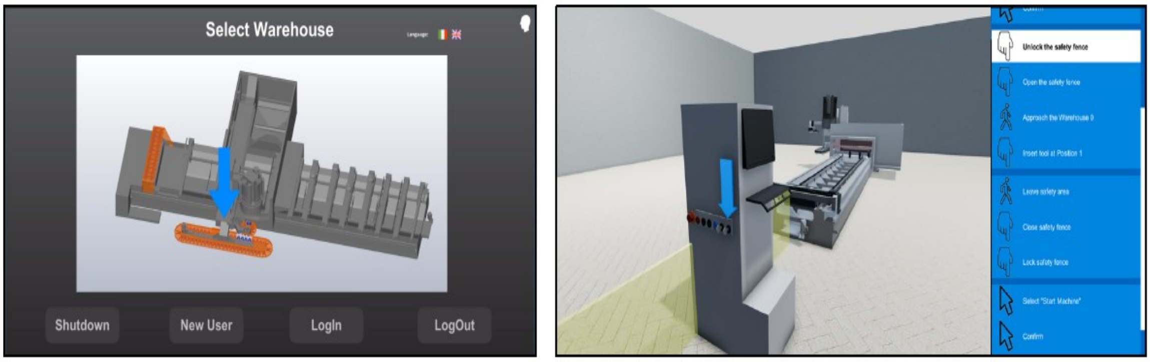


Figure 17: Screenshots of the GUI (left) and the virtual training environment (right)

For the ADAPT module of the INCLUSIVE system, an HMI was developed, allowing users with different capabilities to efficiently use of the machine. In SCM, the aim of this user interface is to assist users, in setting the configuration of the tool warehouse of the machine.

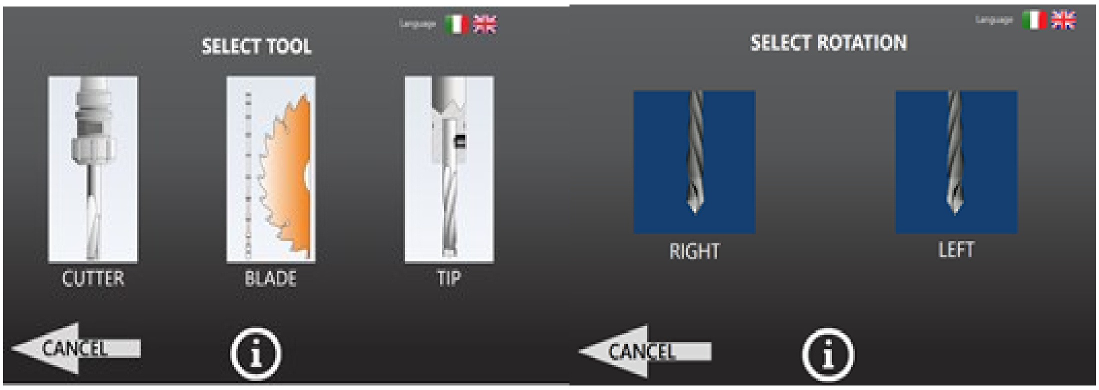


Figure 18: Enriched information provided through the ADAPT module for non-expert users

Thirdly, a portable interface has been introduced to better assist operators when tooling the machine, and when fixing certain machine failures. The HTML-based support system is provided on a tablet that the employee carries.

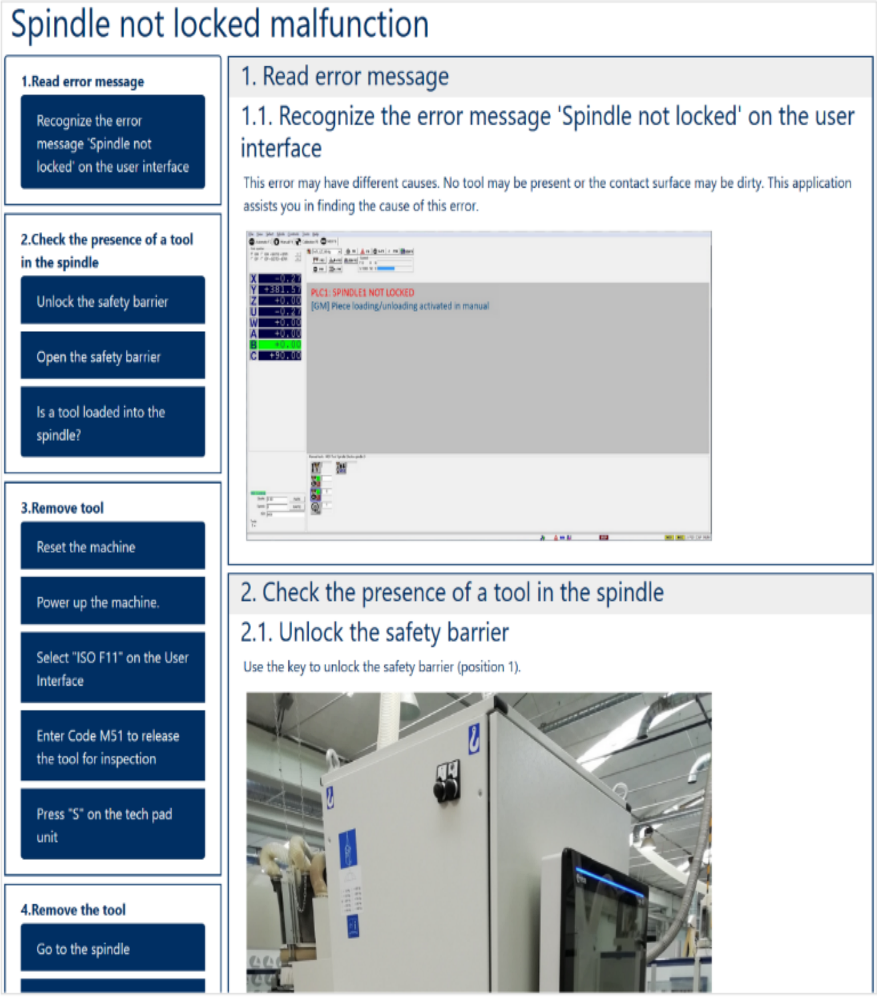


Figure 19: On-line training screenshot

Finally, an EMPATICA wristband has been configured to interact with the Adaptive HMI within SCM, for monitoring the strain status of the operator.

Impact: The use of the INCLUSIVE HMI leads to a 4.2 % reduction in the average time required. For the second use case, the use of the INCLUSIVE HMI leads to a much larger decrease in execution time of 69.7 % when compared to the current HMI system. Moreover, a usability questionnaire has been filled in by testers, allowing to conclude that the INCLUSIVE HMI was perceived as an improvement with regards to the current HMI for all dimensions, for instance frequently usage, complexity, ease of use, functions, consistency, and learning effort.

Lesson learned: Further studies are being carried out to employ the virtual training in order to train the customers' operators without having to wait for the delivery of a newly bought machine, or without having to block a productive machine for training purposes. The ADAPT module will be further developed in order to evaluate integration with the recently released MAESTRO Active HMI, which already incorporates personalization features such as language settings. Finally, discussions are underway with the commercial area in order to verify whether the use of wearables by customer's workers can be promoted in order to improve their well-being at home.

4.18 SILVERLINE use case: introduction of a robotic cell in the production shop floor

Challenge: Silverline produces built-in appliances. Its production process uses several kinds of very simple machines for bending metal parts and components, which were manually fed mainly because of the variability of the process itself and the lack of skilled personnel, in the production line, able to manage automatic machines or robots. In fact, despite SILVERLINE being a large company that exports in the entire world, it is operating in a central region of Turkey, where the population still has, on average, a low level of education. The introduction of robots, although very challenging in terms of production speed and precision, had always been rejected due to their programming and reconfiguration difficulties.

Figure 20: Operators at work

Solution: A system, easily reconfigurable and programmable, with a combination of a robot and a panel bender has been built-up. The HRI developed is able to adapt automatically to the operator's skills, impairments or stress/tiredness.

Impact: The introduction of the hybrid robot/bender panel system allows to reach production efficiency and accuracy, and a more flexible interchange of operators with different characteristics.

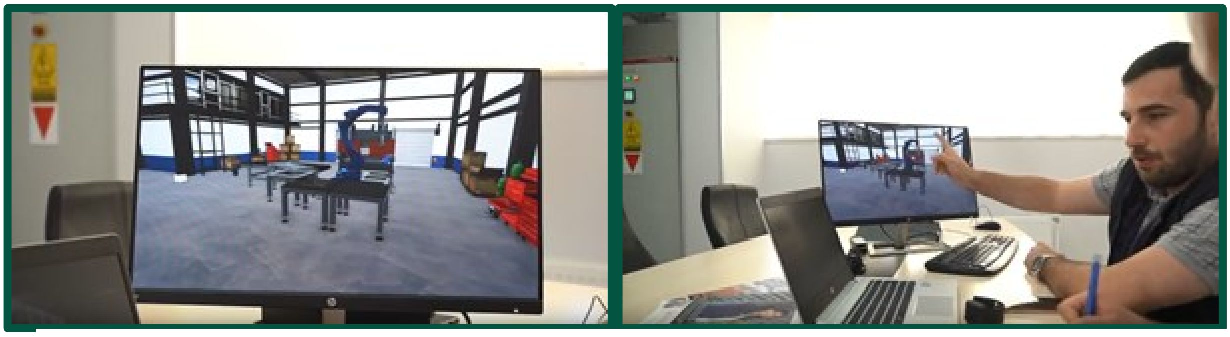


Figure 21: VR tool for off-line training

Lessons learned: Even if robots are well known in Europe there is a lack of knowledge on their real potential and on the existence of tools able to simplify their programming and reconfiguration. Most Industries need to be supported in the process of introducing such tools in the plants. Advanced tools for training, are essential to support the uptake of automation processes.

Figure 22: The Robot/Bender panel

4.19 E80 use case: management of intralogistics flows in complex production lines

Challenge: This E80 use case tackles the problem of the management of a complex production line serving for diversified production. In factories where complete flow automation is needed, E80 LGVs are capable of handling finished products, and packaging materials to be supplied to production lines.

Solution: A smart HMI has been designed that supports the management of automated vehicles for the transportation of goods, compensating variations in role, skills, cognitive capabilities, disabilities, education level and age of operators. Physically impaired subjects are also involved in planning activities, for which little mobility through the plant is required (in situ repair jobs should be handed over to other operators).

Figure 23: LGV fleet

Impact: The customisation capability reflects in terms of reduced vehicles downtime and increased assignment of supervision jobs to vulnerable users. Moreover, the maintenance phases are shortened resulting in less downtime that provides an increase of the productivity of the total system (human and automation).

Lesson learned: The smart HMI was tested in E80, with expert and non-expert operators working on an AGV in real working environment. The availability of such a tool to guide the use and maintenance of complex vehicles was strongly appreciated by workers, since it simplifies the interaction with the vehicle proprietary user interface and enable structured access to knowledge of specific

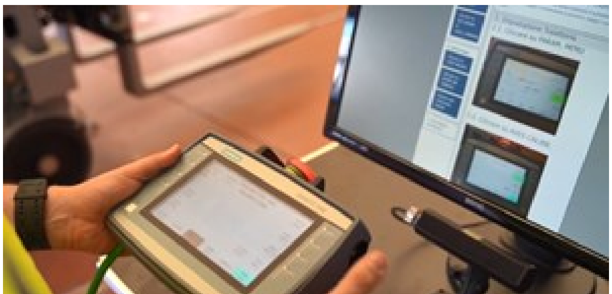


Figure 24: Electric 80 training on the new HMI

procedures that have been carried out empirically. Moreover, expert operators are now able to take advantage of their experience and plan ad hoc maintenance plan, customized on the current status of the fleet.

4.20 Prima Power pilot case: Worker feedback Dashboard - empowering feedback on work well-being and achievements

Challenge: In the increasingly digitalized working environments, workers easily lose sight of what they achieve at work. However, positive feedback on work performance, as well as recognizing personal achievements and development at work are important for work motivation.

Solution: A web-based solution is proposed for providing data-driven, personal feedback to factory operators. The solution focuses on creating awareness, tracking daily accomplishments, demonstrate progress and development of work, generating feedback based on automatically collected data, e.g. an activity wristband etc. The feedback is only for the worker's personal use, and not accessible to the employer. (Heikkilä et al., 2018).

Figure 25: Piloting Worker Feedback Dashboard with the operators of PRIMA Power machines

Impact: The proposed solution aims at raising spirits at work, by helping employees recognize their strengths as well as their development needs. In the long term, the application can assist employees to develop their working habits.

Lessons learned: Worker Feedback Dashboard was piloted in three factories with ten workers. For user acceptance, it has been crucial that the workers participated in planning how to use the solution, and what kind of work practices were related to its use. The pilot evaluation results indicate that there are potential lead users for the Worker Feedback Dashboard. Introducing the solution would facilitate showing the impacts and could then encourage those who may be more doubtful to join.

5 Discussion on methods and technology adoption

Industry 4.0 is introducing new tools and new ways of working to factories. Chapter 4 illustrates examples for different types of operators in human-centred factories as they have been applied in ACE Factories cluster industrial use cases. This chapter concludes and discusses the lessons learned in the ACE industrial cases for different types of operators 4.0.

Virtual and augmented operator. The ACE industrial pilot cases have shown that operators in future factories can utilise augmented reality-based tools to get contextual, hands-on guidance on assembly and other tasks. The guidance should be designed such that it supports on-the-job learning, based on the operator's skill level, and should support his/her personal competence development plans. ACE pilot cases have demonstrated that virtual factories can support training in factory operations in a realistic environment, irrespective of time and place, well before the actual factory environment is available. Virtual factories support training safely, even in exceptional situations such as error recovery. The combination of simulation and virtual factory models brings a large number of proven advantages such as deeper understanding of the whole factory and reduces commissioning ramp-up times and the need for testing of proposed changes. Moreover, the industrial pilot cases have showcased that virtual reality technologies are valid tools to support participatory design, because they support common understanding and collaboration among designers and users. Co-design can be supported by providing environments where ideas can be visualised and even experienced in practice using virtual reality technology. These kinds of co-design solutions were extremely well accepted by the workers in the ACE pilot cases.

Social and collaborative operator. Workers possess a lot of tacit knowledge regarding good work practices and problem solving. Making this knowledge visible and accessible with social media-based tools has the potential of complementing the guidance provided by official documentation and formal practices. ACE pilot cases have indicated that connecting the knowledge to the manufacturing environment context, so that workers have access to situationally relevant information in situationally relevant form, may further ease sharing and accessing knowledge. Operators and the whole work community are engaged to influence their own work environment with knowledge sharing tools that provide motivations for giving practical advice and hints to colleagues. Collaboration tools also support co-design of the production environment utilising the individual expertise of all stakeholders. Integration of production data and knowledge sharing data is beneficial in terms of timesaving and user acceptance. In this way, knowledge sharing tools may become an integral part of the production environment rather than separate tools. In the same context, gamification provides tools to motivate workers to share knowledge. ACE pilot cases have shown that knowledge sharing tools will require changes in organizational practices and policies for content moderation and utilization.

Future workplaces are bringing factories where humans and *robots* work together, sharing work on a single task, collaborating and complementing each other in different production tasks, combining workers' dexterity, flexibility and problem-solving skills with robots' repetitiveness, speed and precision. Robot based solutions are well accepted when they relieve operators from physically demanding or repetitive tasks. However, further work should be performed for improving trust in the design of human-robot collaboration applications since trust is a key-aspect in human-robot collaboration.

Super-strong operator. The usage of *wearable apparatus* like exoskeleton devices has shown the potential to reduce operator's physical fatigue, increase their overall safety and productivity. Future workplaces studied within the ACE Factories cluster introduced exoskeleton devices that support operators within their everyday physically demanding work activities, in an integrated way, using reasoning. The exoskeleton devices that have been developed are able to adapt to the working conditions as well as the current physical status of the operators, utilizing data related to their physical fatigue coming from wearable devices.

Healthy and happy operator. The results of ACE pilot cases have shown that human-centred factory solutions have positive impacts both on operator wellbeing and productivity. Wearable devices provide ways to monitor operator wellbeing and work performance. Getting personal feedback on work well-being and work achievements can be motivating. Special attention needs to be paid to giving positive, encouraging feedback. Workers should participate in designing these kinds of feedback solutions and the work practices related to using those solutions should be agreed with the workers. Workers should have the tools to control access to their personal data according to GDPR regulations. For ethical reasons, using solutions that monitor people's wellbeing and/or work achievements should be voluntary.

One of a kind operator. The Operator 4.0 paradigm shift cannot succeed just by introducing new technologies to the factory floor. Work processes need to be reshaped and new approaches to training are needed in order to support continuous development of skills. ACE pilot cases have shown successful examples of how the personal capabilities, skills and situational preferences of individual operators can be taken into account. When building and utilising user models, privacy protection is essential. GDPR regulations give good guidelines for issues to be taken into account. Operators should be supported in taking responsibility for the development of their competences, and they should receive motivating feedback on their work achievements. The adoption of the solutions is supported by local co-design, where operators are given opportunities to influence the design decisions, and user acceptance of the solutions is studied throughout the development process.

6 Conclusion and Recommendations

Based on the accumulated experience of the ACE Factories cluster technologies development and validation in industrial cases, a number of recommendations for people in academia, industry practitioners and policymakers acting at the local, national and EU level is provided in this chapter. Based on practical and scientific evidence, the recommendations aim to promote practices that improve human factors in manufacturing, while not putting typical production performance targets at risk. This can be achieved on the one hand by industrial practitioners investing in the proposed relevant technologies and practices adapted to their specific needs, and on the other hand by policy makers who can direct actions to areas where further support is needed, or making sure that the proper regulatory framework is in place. The key results of the human-centred factory solutions can be summarised in the following table.

I. Productivity in tandem with wellbeing	1. Human-centred factory solutions will increase both productivity and worker well-being 2. New technical solutions for the real-time measurement of operator's capacities/mental strain and automatic work adaptation contributes to improving productivity and worker wellbeing 3. New technical solutions for real-time measurement of operator's physical strain and automatic adaptation of level of physical support may improve productivity and operator's safety 4. AR and VR are efficient tools for training on the job, which increases the productivity and the workers' wellbeing 5. Providing factory workers ways to influence and improve their work will increase work motivation and productivity
II. Work roles	6. Changing work roles should be implemented with consideration of the needs of elderly workers - no one is left behind 7. New work roles in manufacturing industry should be promoted to young people and those of differing abilities.
III. Ethics, privacy and trust	8. Ethically sound adaptation solutions support the aim of sustainable and responsible industry 9. The know-how of industrial workers must be protected from unauthorized use especially by data and analytics companies. 10.Criteria related to trust in the human-robot cooperation (HRC) should be unavoidably considered
IV. SMEs support	11. SMEs should be supported in adopting human-centred factory solutions

Table 4: List of ACE Factories cluster recommendations

Human-centred factory solutions will increase both productivity and worker well-being

The results of the industrial pilots in the ACE Factories cluster projects show that human-centred solutions are worth adopting as they will have positive impacts both on worker well-being and productivity. Human-centred work environments will directly contribute to one of the three principal dimensions of the Organisation for Economic Co-operation and Development (OECD) job quality index – quality of the work environment – which reduces job strain and health risks.

New technical solutions for the real-time measurement of an operator's capacities/mental strain and automatic work adaptation may improve productivity and worker well-being

Nowadays, as proven by the use cases presented, some technical solutions for the measurement in real-time of the capacity or the mental strain of operators and consequent work tasks adaptation are available at least at the prototype level. As a matter of fact, the capacities of an operator can change very quickly (e.g. usually young people have good learning ability) and the mental strain can vary from hour to hour (e.g. a headache is enough to change concentration level). Systems that are able to detect these changes and adapt should be promoted as drivers of the operators' well-being and productivity enhancement.

New technical solutions for real-time measurement of an operator's physical strain and automatic adaptation of level of physical support may improve productivity and the operator's safety

The concept of operator 4.0 involves the adaptation of the workplace to the operator's needs. Some technical solutions presented above allow the monitoring of the physical fatigue by analysing real-time biometric data, and the adaptation of the level of physical support provided to operators using exoskeleton devices. This may lead to reduced work-related musculoskeletal disorders while simultaneously improving productivity and safety.

AR and VR are efficient tools for training on the job, which increases productivity and work wellbeing

A fundamental enabler of new technology adoption is training on the job, both off-line and online. The use of AR and VR technologies as well as Artificial Intelligence, are radically changing and improving training techniques. To ensure a rapid transition to these new techniques specific measures for their support should be taken.

Providing factory workers with ways to influence and improve their work will increase work motivation and productivity

Factory workers are very willing to influence their own work and workplace. That can be seen in the high acceptance level of knowledge sharing and participatory design solutions. When people can influence their work, they experience their work more meaningfully and they commit to the new practices and tools. Motivated workers are also more productive.

Moreover, the participation and involvement of workers in the whole cycle of adopting new human-centric solutions, or in the improvement of existing ones, in which they are able to contribute their own individual expert knowledge, can be the key to success.

Operator 4.0 solutions support continuous, individual learning. This should be supported by individual competence development targets and regular follow-ups. If workers are willing to take responsibility for their own competence development, it should be supported. Still, it should be recognised that not all individuals have professional ambitions, which should also be accepted.

New work roles in the manufacturing industry should be promoted to young people and those of differing abilities

The new work roles in industry should be promoted, so that young people have a realistic image of future factory work and are encouraged to choose factory work as a career. Similarly, the potential futures of those with different / more limited abilities should be accommodated as far as possible in more inclusive future manufacturing environments. Providing good opportunities for a wider and more diverse population of workers is a responsible goal for all organisations. In assembly jobs, Industry 4.0 technologies (specifically collaborative robotics and AR) can be used to help reduce the levels of experience and qualification required from a worker to carry out a job. Candidate worker capacities that may benefit from such interventions are visual memory, similarities and differences, spatial orientation, numerical literacy, learning of tasks, reading skills, attention, rhythm, responsibility.

Changing work roles should be implemented with consideration of the needs of elderly workers - no one is left behind

The changing demands of new work roles in increasingly automated and digital manufacturing should not leave existing workforces behind. Older people will have a wealth of experience and knowledge that should not be lost but redirected and utilised. More inclusive opportunities for younger, older, and more diverse workers should be provided that will directly contribute to two of the three dimensions of the OECD job quality index: earnings quality (level and distribution of earnings) and labour market security (minimising risk / duration of unemployment).

Ethically sound adaptation solutions support the aim of sustainable and responsible industry

Industrial work can be improved by adapting the work according to the individual skills and expertise of employees. Advanced adaptation solutions have the potential to compensate for the physical and cognitive capacity of the worker during his/her whole work career. Human factors measures such as usability and satisfaction can be applied in the design and implementation of these solutions for this purpose. This supports the aims of a sustainable and responsible industry.

Monitoring and measuring workers is a new and complex phenomenon that introduces several legal, ethical and company policy related issues. GDPR regulations give good guidance for implementing solutions that protect the privacy of individual workers. The solutions and the related company practices still need to be designed locally at workplaces involving operators and other stakeholders. A negative impact of worker monitoring could be that the tools would be used for performance management. This should be avoided by carefully designing and providing transparency of the whole data cycle and its management.

The know-how of industrial workers must be protected from unauthorised use especially by data and analytics companies

Introducing advanced data collection and analytics technologies with the aim of supporting the capabilities of industrial workers imposes certain risks. The tacit knowledge of industrial workers could be overtaken by Big Data platform providers and this could lead to workers losing their skills, as their know-how will be captured by advanced Artificial Intelligent systems and can be applied using advanced robotics.

Criteria related to trusting human-robot cooperation (HRC) should be unavoidably considered

The design and development of an HRC system has to be carried out following a user-centred methodology that involves human stakeholders throughout the process. Although safety is the key factor in such systems, it is no longer enough. User experience needs to be optimised as it is a key determinant of acceptance and, therefore, of the human-robot system performance. The workers need to trust that it is safe without the fences and physical safeguards that have traditionally kept robots segregated and safe. Workers will now need to feel safe and comfortable without these physical barriers so achieving the right level of trust is crucial.

SMEs should be supported in adopting human-centred factory solutions

The concept of operator 4.0 is still quite new and there is a need to raise awareness within the industry, in particular amongst SMEs that have little inclination to invest in technologies and methodologies that do not have an immediate return on investment (ROI) and that are not imposed by large customers. Furthermore, SMEs are also less likely to have access to methods of measuring workers' needs to promote satisfaction and motivation.

As a consequence, the new technical enablers may increase the digital divide between large companies and SMEs. Targeted actions to raise awareness among SMEs and support the adoption of new human-centred solutions should be developed.

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