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# Adaptive automation assembly: Identifying system requirements for technical efficiency and worker satisfaction

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ABSTRACT

Manual assembly work systems bring high flexibility but low productivity in comparison to fully automated systems. To increase productivity but maintain flexibility, future systems need to incorporate greater levels of automation which complement or augment the capabilities of the human operators who provide the manual work. Future systems should be designed for social and economic sustainability within fluctuating conditions and for adaptive utilisation of operators' individual capabilities to maintain levels of productivity and personal satisfaction. To successfully create such systems with greater adaptivity and interactivity between people and technology a comprehensive understanding of design requirements is needed; the current problem is that there is no standard valid framework. The work described in this paper employed a three-component investigation to identify the various key requirements that are needed to form such a design framework for future human-automation assembly systems. This involves separate activities with different methodologies involving literature reviews, surveys and business case analysis to define use case scenarios and requirements for creating adaptive automation assembly system demonstrators. The different methodological approaches and results for all of the three component studies are described, along with conclusions and implications for further research work and for industry in general.

## 1. Introduction

In a context of ever-changing demands, today's manufacturing systems need to be increasingly flexible and responsive to deal with fluctuating market demands and customisation trends (Hu, 2013). This brings the need for systems to be reconfigurable with a range of digital technologies and intelligent automation/robotics that will enhance system adaptability and minimise the efforts needed for setting up and executing operations (Chryssolouris et al., 2009). To meet this challenge, the Industrie 4.0 'revolution' is driving the development and implementation of new technologies and automation for more adaptive systems (Hermann, Pentek, & Otto, 2016).

Despite increasing digitisation and automation, assembly systems continue to require manual labour because many human qualities, such as the ability to cognition and problem solving, are still irreplaceable (Wyman, 2017). In Industrie 4.0 'smart factories' people will typically remain the most flexible part of production systems, which means the systems are not being designed to eliminate but to support them with new technologies that can enhance their capabilities and compensate for any limitations (Hermann et al., 2016; Romero, Bernus, Noran, Stahre, & Fast-Berglund, 2016; Weyer, Schmitt, Ohmer, & Gorecky, 2015). Thus, future assembly work systems will involve unprecedented levels of socio-technical integration and reconfigurability – putting people and technology together to take advantage of each other's strengths, which not only requires consideration of technical specifications but also the needs of human operators (Fast-Berglund & Stahre, 2013). Although formal standards and specifications for performance and safety of industrial systems exist, they are typically outpaced by advances in technology and include little consideration of non-technical human requirements (Faber, Bützler, & Schlick, 2015).

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A number of recent literature reviews have been conducted to classify the key components, systems and technologies of Industrie 4.0. However, because these classification models have been derived from different approaches, different questions and different scales their diversity makes it difficult to identify a most suitable or valid framework. For example, Hermann *et al.* (2016) reviewed 51 research articles to define principal components of Industrie 4.0 and identified the following:

- Cyber-Physical Systems
- Internet of Things
- Internet of Services
- Smart Factory

These four categories are clearly at a high level and will contain a wide range of sub categories and individual factors that may or may not be relevant to different contexts. However, the authors also further identified six design principles that they propose can be used to guide system implementation:

- Interoperability
- Virtualisation
- Decentralisation
- Real-time capability
- Service orientation
- Modularity

These design principles are also at a high classification level and would, therefore, clearly need to be evaluated and applied according to their relevance to the requirements of particular contexts. In a slightly different approach that looked at what research has prioritised and investigated, Lu (2017) reviewed 88 scientific papers related to Industrie 4.0 and identified that five principal categories have been of most interest:

- Concept and perspectives of Industry
- Cyber Physical System (CPS) based Industry
- Interoperability of Industry
- Key technologies of Industry
- Applications of Industry

Similarly, Fast-Berglund, Mattsson, and Bligard (2016) investigated key components of Industrie 4.0 from the research perspective but this time on a much larger scale. They reviewed over one thousand research articles and coded them according to whether the content was deemed most relevant to Human, Automation, or (human-automation) Interaction. They then coded a further 690 sub-categories from which they identified those that appeared most frequently, as below:

- Human-centred
  - o Situation awareness
  - o Decision making
  - o Human errors
  - o Trust/automation reliance
  - o Mental workload
- Automation-centred
  - o Performance (operational)
  - o Level of automation (degree, type and stages)
  - o Function allocation
  - o Flexibility
- Interaction-centred
  - o Safety
  - o Control
  - o Design

This model provides a more detailed breakdown of the specific aspects of Industrie 4.0 human-system interactions that should be considered in design and evaluation of future assembly work systems. However, as these three recent examples show, high level classifications would require much finer-detailed analysis to link individual factors to the technological requirements of real examples. Moreover, models such as these that are derived from reviews of previous research may not incorporate analysis of multidimensional requirements, i.e. the opinions from different user/stakeholder groups which will be important to gaining successful user adoption.

Taking all of these factors into account, the immediate research problem is that there is a need to better understand specific human and technology requirements of future assembly systems for design and implementation purposes. Existing knowledge and recently produced models for Industrie 4.0 are not sufficiently valid or comprehensive as they are typically not based on user and stakeholder opinion, multilevel requirements, or factors that are directly relatable to specific characteristics of the context in hand.

The paper presents the preliminary work and findings of a large-scale project that is currently developing this level of understanding for the creation of a new generation of sustainable, evolvable socio-technical assembly systems. The A4BLUE project (www.a4blue.eu) will develop a set of assembly system use case scenarios (two industrial and two laboratory-based) in which digital and automated mechanisms are integrated to respond to changing production demands and conditions, including worker variability. These systems will demonstrate important innovation for future assembly systems in that they will be designed to incorporate context-aware interaction mechanisms and a rule based model of worker satisfaction. The aim is to provide personalised assistance that optimises efficient task execution and worker wellbeing. However, in order to create systems that integrate these innovative and user-centred features it is essential to begin with a better understanding of design requirements. To this end, exploratory research work has been conducted to elicit key design requirements for future socio-technical assembly systems. This investigation comprised three parallel but separate component studies with different methodological approaches:

- *Benchmarking for the Design of Use Case Scenarios*; a literature review and survey to define the current state of the art for assembly systems technologies and predicted future trends for the design of the use case scenarios/demonstrators
- *Multidimensional User Requirements Analysis*; a literature review and survey to capture design requirements at both 'high level' (regulatory/external to organisation) and 'user level' (stakeholder/organisational)
- *Business Case Requirements Analysis;* a business case assessment of specific requirements for the four use case scenarios in the project, identifying the main challenges and main objectives for each

The overall aim of this work is to identify the various and multi-dimensional requirements that should be considered in the design of future assembly work systems involving human-automation interaction. The reason for this endeavour is to optimise the design of work for human operators in the future, to maximise their performance capability and satisfaction/wellbeing. To achieve this aim, three separate component studies are conducted in order to capture types of requirements from across different levels of sources and contexts. This paper describes the work, summarising key aspects of its various methods and results. The purpose of the paper is to demonstrate the potential contribution that we can make by defining key requirements for the design of future systems and, ultimately, collating a design framework for manufacturing in general in the 4.0 era.

For the purposes of distinction and clarity, this paper is structured to first present each of these three parallel exploratory component studies separately, but then at the end bring together a united summary of the overall output. Thus, the following three sections describe the three

components in turn so that the purpose, method, analysis and results of each approach is self-contained; then a combined overall summary of results, conclusions and implications for further work is finally presented.

## 2. Benchmarking for the design of use case scenarios

The benchmarking activity was conducted to define the current state of the art in assembly systems and applied technologies and compare this with predicted 'future' trends to inform the down-selection of appropriate technologies for the project's use case scenarios. To improve upon the shortcomings of existing models found in recent literature, as described in Section 1, this comprised of a literature review that focused on current and future technologies that were known to be relevant to the specific characteristics of the project's use case processes and was complemented by a bespoke stakeholder opinion survey.

### 2.1. Method

#### 2.1.1. Literature review

Available relevant literature – scientific and industrial – was extensively reviewed. Due to the volume of articles that have been published in recent years on topics related to human-system interactions in Industrie 4.0 and smart factory systems, and the large diversity of the methods and analyses reported, a direct comparison of findings and research quality is difficult. Thus, a small snapshot of exemplar items is provided to illustrate the current state of the art in knowledge. The findings are organised within a set of seven principal technology categories that reflect commonality in the literature coupled with relevance to the specific context of this project's use case processes:

- Electronic Lifting Aids/ Exoskeletons (Lifting Aids)
- Adaptive/ Self-Learning Production Control (Prod Control)
- Collaborative Robots (Cobots)
- Driverless Transportation Systems (DTS)
- Augmented Reality/ Assisted Reality/ Virtual Reality (AR)
- Interactive/ Adaptive Interaction Mechanisms (Interaction)
- Optical Control Systems (Optical Control)

#### 2.1.2. Survey

To complement the literature review, a small survey was designed to make an initial exploration of the current use and perceived benefits of the identified technologies. The survey format begins with a description of the project aim and requirements, along with ethical assurance of full confidentiality which is enabled by its anonymous online format, and in accordance with Regulation 2016/679 of the European Parliament. The survey then consists of two sections. The first section is made of nine multiple choice questions that ask the participant various questions to obtain profile information primarily to identify the sector and type of organisation they represent, to ascertain what/how existing automation and technology is currently used in that domain, and to describe current limitations. The second section contains six further questions that seek opinion ratings about adaptive workplaces and related technologies. Four of these questions include a 5-point Likert agreement scale which ranges from slightly disagree to strongly agree. Three questions in particular are used in this paper to reflect key indications of opinion: one asks what technologies are currently 'in use' within the participants' company, another asks which technologies have provided most improvement to processes and are therefore most 'useful', and the third asks the respondent to indicate which technology they consider to be most 'important' in the future.

The original English version of the survey was translated into Italian, Spanish and German versions and uploaded into its online format. The electronic link to the survey was distributed by industrial and scientific partners via corporate communications and personal emails, and by the designated A4BLUE project dissemination routes, i.e. through a dedicated website page and in a published newsletter. As this survey was administered using an online platform there is no reliable means of calculating how many candidates were approached and declined. However, 91 responses were received automatically through the system. Out of ten options provided, most participants represented four main industrial sector categories: Aerospace, Automotive, Information and Communications Technology (ICT), Manufacturing and Industrial Process. The survey questions also enabled differentiation between seven types of organisation, but the respondents predominantly represented large enterprises, small and medium enterprises, and research organisations.

### 2.2. Results

A summary of overall % participant responses are first presented to provide a snapshot of the current state of technology use. Then, in sections pertaining to each of the individual identified technology categories, selected exemplar findings from the literature review are presented alongside selected overall results of the benchmarking survey. A series of tables, one in each technology section, provides the descriptive summaries which illustrate collective scores regarding opinions on the technology's current level of 'in use' application, its current level of 'usefulness' and, finally, its predicted level of importance in future assembly processes. All of these summaries depict responses from the same sample with no missing data (n = 91). The aim of these summaries is to provide a reasonable indication of the current state of the art, in terms of what technologies are being used by organisations at the present time, as well as indications of likely future application.

#### 2.2.1. Current technology use

Fig. 1 below illustrates the extent to which participants representing the dominant industrial sectors reported that their organisations currently use technologies in the given categories. It can be seen that optical controls are the primary new technology being used at the current

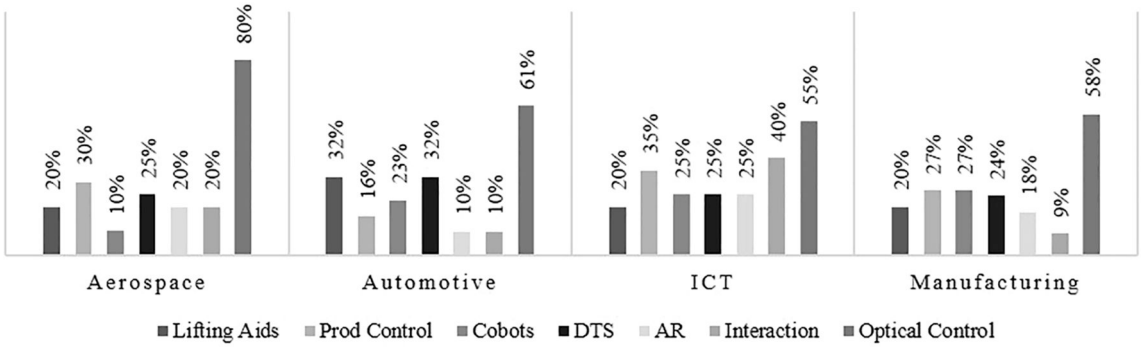



**Fig. 1.** Reported use of new technologies being used across principal industrial sectors.

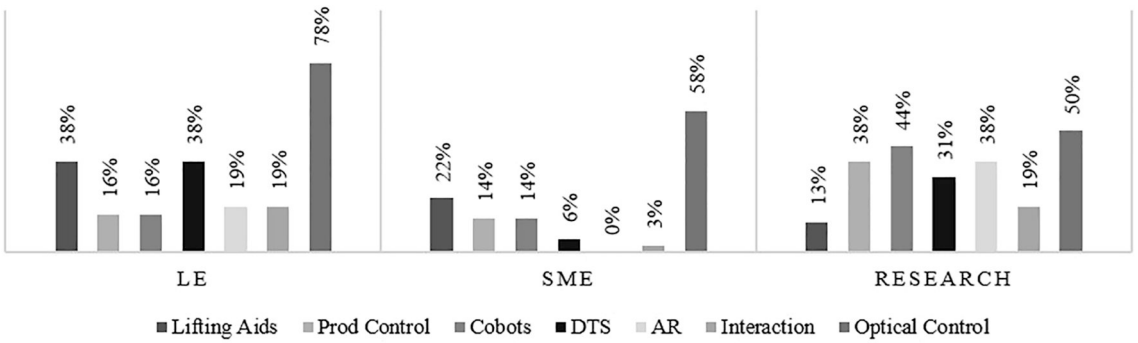



**Fig. 2.** Reported use of new technologies being used across type of organisation.

time across these sectors.

In terms of organisation type, Fig. 2 summarises the extent to which participants reported using new technologies from the dominant categories of large enterprises (LE), small and medium enterprises (SME) or Research establishments.

Fig. 2 shows that, once again, optical controls appear to be the main technology being used in industry whereas, as would be expected, research organisations are exploring a range of other new technologies more evenly. SMEs are customarily generally using less new technology than larger (and richer) industrial organisations, particularly with respect to applications of augmented reality (0%), interaction mechanisms (3%) and driverless transport systems (6%).

These results provide an indication of current technology use across industry and research organisations. Evidence found in the literature and in the benchmark survey results is now presented for each of the seven technology categories.

### 2.2.2. Electronic lifting aids

*2.2.2.1. Literature.* Work-related musculoskeletal disorders affect about 44 million EU workers per year who primarily work in jobs that require physical lifting and poor posture, and this is leading to total annual costs of over 240 billion euros/2% of GDP to the European economy (Bevan, 2012). However, many of these work activities cannot be replaced with automation/robots as they are still too complex and variable to be standardised. To address this problem much research effort in recent times has been directed to develop wearable electronic lifting aids powered by electric motors, pneumatics, springs or hydraulics to increase the strength and endurance of the user. An example of research development in this area is the Robo-Mate project at Fraunhofer IAO, Germany which is developing a prototype exoskeleton to reduce lifting and carrying loads by up to ten times (www.robo-mate.eu). In the industrial sector, ergonomic 'chairless chairs' are another recent area of technology under development, to provide portable wearable structures that enable operators to sit at any time during assembly work (Schembera-Kneifel & Keil, 2016).

*2.2.2.2. Survey.* Fig. 3 shows that the benchmarking survey results indicate electronic lifting aids have their peak distribution in the automotive industry and by larger companies which is understandable given that the perceived benefits and importance is expected to be higher in sectors with heavy goods and greater capital. However, the aerospace industry participants predominantly considered lifting aids to be important in the future indicating a likely increase in forthcoming applications.

### 2.2.3. Self-Learning production control

*2.2.3.1. Literature.* In times of shorter response time-to-market opportunities, increased product variations and rapid changes in product demand (Di Orio, Cândido, & Barata, 2014), concepts of adaptive production control are becoming increasingly important for assembly systems to adjust to new circumstances and rapid changes in the dynamics of processes (McKay & Buzacott, 1999). By integration of control and maintenance processes as part of context awareness, maintenance costs are reduced and the overall equipment effectiveness, such as system availability and productivity, can be improved (Uddin, Dvoryanchikova, & Martinez Lastra, 2011). Related research topics in this category include the reduction of process time, effort and errors, a high degree of flexibility, the reduction of down times during product exchange and increased overall equipment effectiveness (Le-Anh & De Koster, 2006).

*2.2.3.2. Survey.* Fig. 4 shows that current applications of self-learning production control are mainly occurring within research rather than in industry. However, it is considered to be an important technology of the future by around 50% of the respondents spanning across each industrial sector and organisation type. Large companies show a slightly higher interest while small companies appear less convinced.

### 2.2.4. Collaborative robots

*2.2.4.1. Literature.* Collaborative robots or 'cobots' are described as "mechanical devices that provide guidance through the use of servomotors, while a human operator provides motive power" (Krüger, Lien, & Verl, 2009). This combination enables exploitation of each partner: robotic force and repeatability with human flexibility and sensitivity. Collaborative robots are already popular and being developed and tested across the manufacturing industry with positive results. For example, collaborative robots introduced to the BMW X3 plant in Spartanburg were found to reduce human idle times by 85% (Knight, 2014).

*2.2.4.2. Survey.* Despite popular industrial interests in collaborative robotics, the benchmark survey results show that they are still rarely being used in current series production across all sectors (Fig. 5). Only research institutions apply them regularly. Nevertheless, they are considered to be highly useful and very important in the future across all branches and company types.

### 2.2.5. Driverless transport systems

*2.2.5.1. Literature.* Driverless transport systems (DTS), mostly used for physical logistics operations, differ in terms of vehicle designs and system structures according to sector and items being transported. They include Automated Guided Vehicles (AGV) for which the main issues are guide-path design, vehicle routing, vehicle requirements, idle-vehicle positioning, battery management, vehicle scheduling and deadlock resolution (Le-Anh & De Koster, 2006). In the automotive industry, permanently installed transport systems with connected large supply areas are widely spread. At Daimler, for example, all required parts are picked/sorted and then brought to the final assembly line by driverless transportation vehicles (Daimler, 2015). Audi have progressed even further and established DTS to transport finished

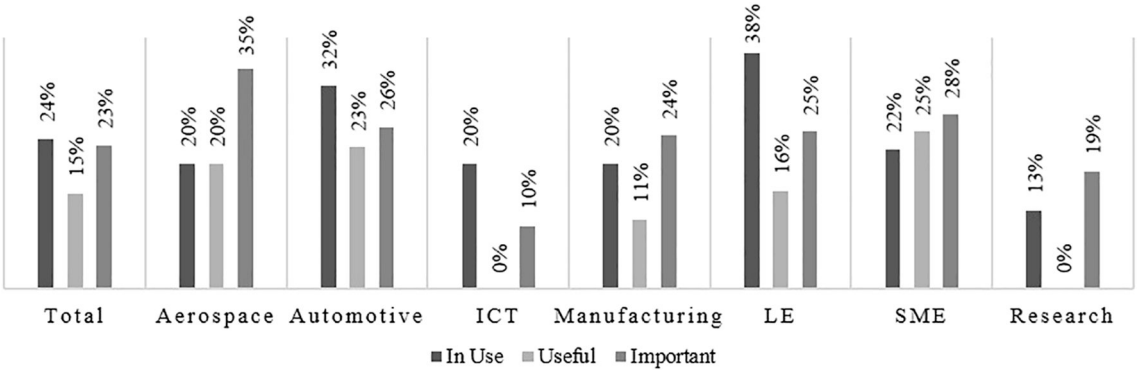



**Fig. 3.** Overall benchmark survey results for Electronic Lifting Aids.

vehicles automatically through the plant (Tredway, 2017).

*2.2.5.2. Survey*. Responses to the benchmarking survey show that the estimated future importance of DTS is fairly evenly distributed at a medium-high level across the automotive, aerospace, and manufacturing and industrial process sectors, and across the different types of organisation in which this technology will be developed and applied (Fig. 6). Reports on current use and usefulness are also fairly evenly spread across sectors, although of notably less relevance to participants from smaller organisations (SME).

*2.2.6. Augmented reality*

*2.2.6.1. Literature*. Augmented Reality (AR) is considered a variation of Virtual Reality (VR), in that while VR immerses the user completely inside a synthetic environment, AR supplements reality with an overlay of information whilst still allowing the user to see and interact with the real world (Azuma, 1997). The possible industrial applications of AR have caused a great scientific interest, such as for virtual training of workers (Schenk, Straßburger, & Kissner, 2005), assembly guidance, maintenance, repair of complex machinery (Azuma, 1997) and information support regarding machine warnings, job orders and part simulation (Michalos, Karagiannis, Makris, Tokçalar, & Chryssolouris, 2016). Studies have shown that AR, when compared to paper-based instructions, reduces assembly process time and failure rates (Baird & Barfield, 1999). Hence, AR is being developed for integration in assembly systems across aerospace and automotive companies such as Boeing (Scott, 2017), Airbus (Wright, 2017), Volvo (Favreau, 2017) and GE (Abraham & Annunziata, 2017).

*2.2.6.2. Survey*. Similar to the survey results for collaborative robotics technology, AR technology is still rarely being used in current production processes despite being of great current industrial interest and research activity, and very few of the participants consider it a useful technology at the moment. Responses show it is considered to be highly important in the future, especially in aerospace and automotive (Fig. 7).

*2.2.7. Interactive/Adaptive interaction mechanisms*

*2.2.7.1. Literature*. Interactive mechanisms refer to the evolution of traditional keyboard-and-screen interfaces into increasingly intuitive methods of interaction such as gestures, speech, haptics and eye blinks based on the mix of different audio visual-signals in human to human communication (Jaimes & Sebe, 2007). Due to the increased integration of technical systems into assembly systems, such intuitive user interfaces need to be provided (Kunz & Wegener, 2015). Truly adaptive forms of interaction use systems that are able to adapt to different operators whereby the system considers the user as well as the assembly task and provides optimal ways of interaction (Norcio & Stanley, 1989). In a current application gestures are being used for quality control and defect identification at the BMW site Landshut (BMW Group, 2017).

*2.2.7.2. Survey*. Fig. 8 shows that the benchmark survey results indicate that many more people in ICT believe in this technology, than in the other sectors. However, the related technologies are generally not being widely used or considered to be highly useful or important in the future across the different industrial sectors and types of organisation by comparison to the survey results for other technologies.

*2.2.8. Optical control systems*

*2.2.8.1. Literature*. Optical systems provide information about items via labelled codes and scanning. The main advantages of these systems are automation of management processes, low-cost application, quick provision and interlinking of information, although the disadvantage of traditional one and two dimensional codes are limited information storage capacity. A sequence of QR (quick response) codes provides the opportunity to use time as a third dimension and thereby increase the

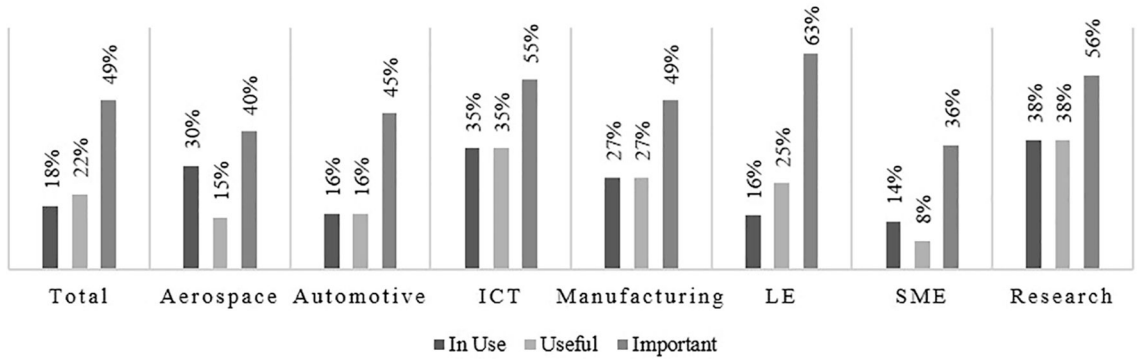



**Fig. 4.** Overall benchmark survey results for Self-learning Production Controls.

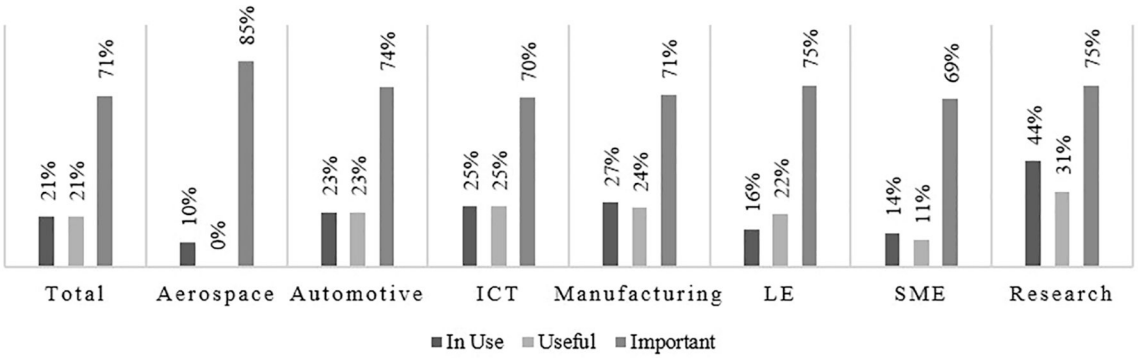



**Fig. 5.** Overall benchmark survey results for Collaborative Robots.

information storage capacity (Memeti, Santos, Waldburger, & Stiller, 2013). Nowadays, scanning of barcodes in logistics is state of the art technology. New approaches integrate the scanner in working gloves, smartwatches or glasses, so that the worker can keep both hands free (Volkswagen, 2016).

*2.2.8.2. Survey.* As shown in Fig. 9, optical control systems are already quite widely used across the industry sectors and the different organisation types, but particularly in large organisations and in aerospace. However, whereas for other technology categories the tendency has been for participants to rate future importance as higher than current use or usefulness, in this case optical controls are being reported as in use currently more than they are considered of use and importance in the future.

Interestingly, participants from large enterprises and SMEs have provided almost identical ratings of this technology being currently useful, at 59% and 58% respectively, but those from smaller companies are anticipating a lower level of future importance.

## 3. Multidimensional user requirement analysis

To ensure the successful design of a work system it is important to incorporate a user-centred design approach to guarantee the needs of the people who will be directly involved in applications of the system are considered, as well as compliance with all relevant statutory requirements and regulations. Therefore, a principal early activity has been to capture both of these 'user level' requirements (stakeholders in the organisation) and the 'high level' requirements (regulations from outside of the organisation).

### 3.1. Method

Different methods were applied to capture user level and high level requirements for the design of new work systems so these are now described individually, in turn.

#### 3.1.1. User level requirements

The selected method for capturing user level requirements was a participant survey because this would enable systematic and consistent collection of stakeholder opinion across different user groups, organisations, and geographical locations. It was important not to focus predominantly on operators but elicit viewpoints from across the various stakeholders who will be affected or be involved in the implementation of new assembly systems; operators will play a significant role in more in-depth human factors analysis and system testing later in the project. The aim of this activity is to reveal more general opinions about the technologies.

*3.1.1.1. Participants.* To maintain a user-centred approach, it was important that participants represented the various stakeholder groups that are likely to be involved in the application of the A4BLUE assembly systems. So, a broad set of relevant user groups were identified across four categories Business, Organisation, Technical and Human. 50 participants completed the survey from France, Germany, Italy, Spain, and the UK, their age spanning 18 to 65 years. Most participants (42%) were between 26 and 35 years, work in the Aerospace sector (36%) and were based in Spain (56%). The composition across the user groups is shown in Table 1. [NB three participants chose to represent two user groups so the response total is 53].

*3.1.1.2. Survey design.* As there is no existing tool for collecting data relevant to all of the planned design technologies of the new A4BLUE systems it was necessary to construct a new bespoke survey instrument spanning the six key topic categories: Organisational level requirements, Automation and robotics, Communication and interaction mechanisms, System feedback and assistance, Systems information and instructions, and System security and data

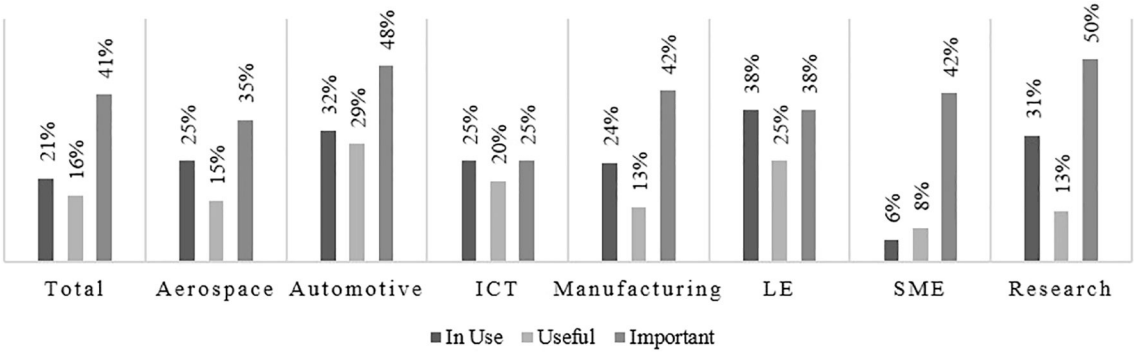



**Fig. 6.** Overall benchmark survey results for Driverless Transport Systems.

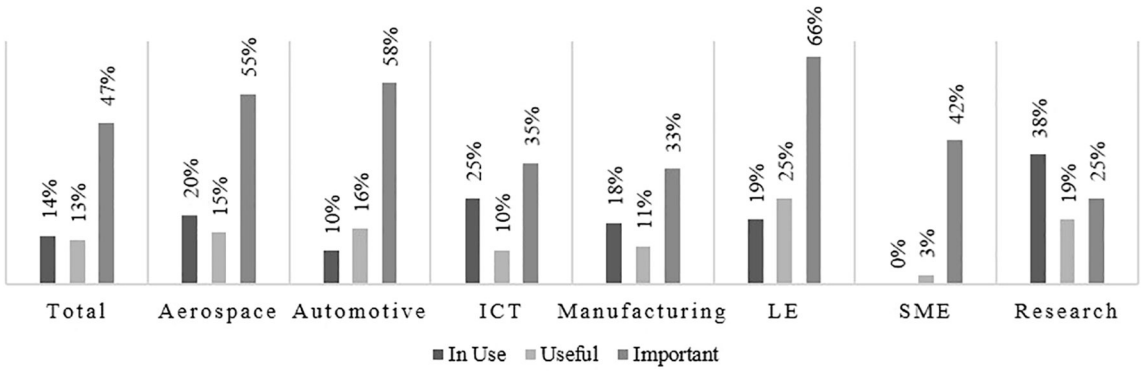



**Fig. 7.** Overall benchmark survey results for Augmented Reality.

management. The survey was intentionally straightforward to enable further adaptation and translation for other project phases. It included opinion measures (quantitative) via subjective ratings on potential technologies and features listed as a set of items (statements), using three simple options: "Essential", "Desirable" or "Unnecessary". Additionally, the survey included questions to derive explanations for the opinions (qualitative) which simply asked to participants to write any further comments and provide further suggestions for design features. Finally, the survey also provided an opportunity for participants to rate any new suggestions ("Essential" or "Desirable") to identify priorities. The original English version of the survey was developed into French, German, Italian and Spanish and uploaded to the EUSurvey (European Commission) online survey platform, then hyperlinks were emailed to potential participants. This method ensured consistent administration and anonymity, enabling reliable comparisons across countries and user groups in full compliance with EU data protection and ethical regulations.

### 3.1.2. High level requirements

To capture 'high level' requirements it was necessary to review documents that set out formal obligations for the design of industrial work systems. As the project is primarily developing systems for the European Union (EU) manufacturing industry, the review focused on relevant EU law (Machinery Directive 2006/42/EC) and associated EU standards governing industrial work and machinery safety. Relevance of material was based on its applicability to four categories linked to the technologies being explored in the benchmarking activity: industrial work and machine safety, automation and robotics standards, ergonomics and human factors, and digital systems.

## 3.2. Results

### 3.2.1. User level requirements results

As the small number of participants prevented statistical analysis of group differences, descriptive statistical summaries for each category are provided in a series of tables, covering each of the survey categories in turn. In these data tables the columns show percentage responses according to the following response options: "Essential" (ES), "Desirable" (DE), "Unnecessary" (UN), "No answer" (NA), and "Overall agreement" (OA; this was derived by adding "Essential" and "Desirable" scores together and calculating the percentage). The results presented below pertain to the responses from all 50 participants (there is no missing data).

*3.2.1.1. Organisational level.* Responses in this category produced a 75% to 100% overall agreement. Table 2 shows that most "Unnecessary" responses relate to items proposing whether future systems should have the ability to self-adjust to compensate for lower operator experience and training and lower technical abilities. However, all items were mostly rated as being "Essential" or "Desirable", indicating overall support for system adaptivity and self-optimisation.

*3.2.1.2. Automation and robotics.* Results in Table 3 show that 17 of the 20 items presented to participants received more than 80% level of overall agreement. The greatest percentage of "Essential" responses were given for items that describe safety mechanisms and the capabilities of automation and robotics. Most "Desirable" responses were provided in relation to the potential for automation and robotics to meet operator and production variations, which further supports designing for flexibility in future systems.

*3.2.1.3. Communication and interaction mechanisms.* Responses in this category achieved an overall agreement profile of 70% or greater (Table 4). Visual feedback was the most preferred format, but auditory and visual systems were also often considered "Desirable". Interaction mechanisms in current practice were popular as "Essential" features, but more innovative functions were also often considered as

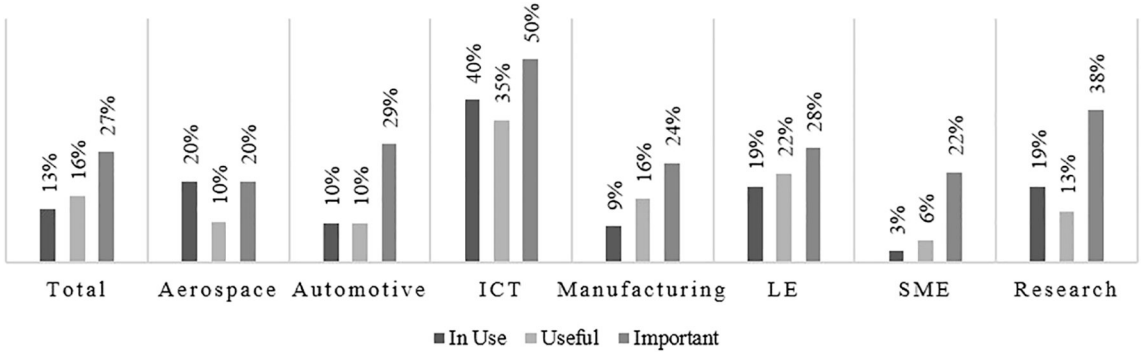



**Fig. 8.** Overall benchmark survey results for Interactive Systems.

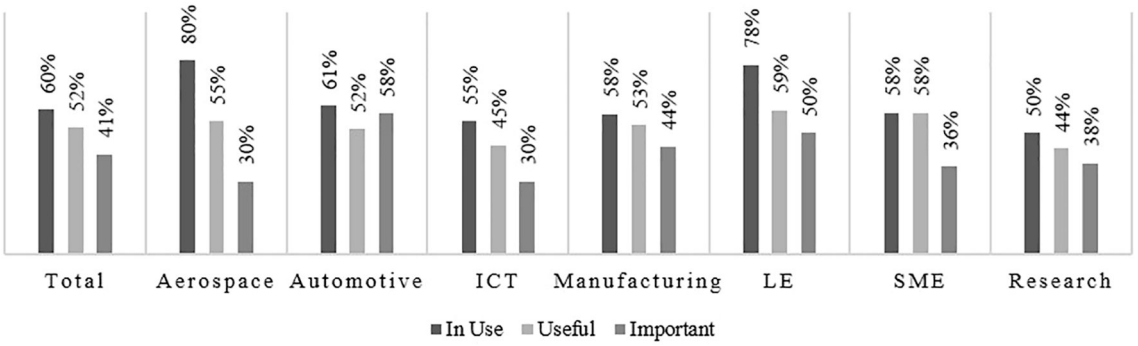



**Fig. 9.** Overall benchmark survey results for Optical Control Systems.

**Table 1**
User requirements survey participant numbers by user group.

| User groups | | Participants | Total per category |
|---|---|---|---|
| Business | Finance/accounts | 1 | 5 |
| | Cost engineering | 2 | |
| | Marketing | 1 | |
| | Customer service | 0 | |
| | Legal | 1 | |
| Organisation | Senior management | 1 | 9 |
| | Production manager/supervisor | 1 | |
| | Operator (shop floor) | 5 | |
| | Maintenance (shop floor) | 2 | |
| | Trade union | 0 | |
| Technical | System design/architect | 2 | 32 |
| | Technology acquisition | 3 | |
| | Technology/system integration | 8 | |
| | IT | 11 | |
| | Life cycle engineering/ management | 3 | |
| Human | Assembly planning | 5 | 7 |
| | Occupational health | 0 | |
| | Human resources | 2 | |
| | EHS | 2 | |
| | Ergonomics/human factors | 2 | |
| | Training and Development | 1 | |

"Desirable". One participant suggested fixed tablet devices for communication and interaction.

*3.2.1.4. System feedback and assistance.* This category reflects technologies that interface directly with operators to aid their execution of assembly tasks. Table 5 shows the overall level of agreement for all items in this category was greater than 78%. Results indicate that just-in-time delivery of tools and equipment would be the preferred option for future systems. Most positive responses related to personalisation technologies, echoing results in the automation and robotics category.

*3.2.1.5. System information and instructions.* This category also represents direct system-operator interface. Table 6 shows that responses generated 80% overall agreement and items proposing the use of novel technologies to present information, and to enable operators to interrogate data, achieved 100% overall agreement. Most "Desirable" scores were related to operator control over information and inputs, but also for individual performance monitoring and feedback. The use of augmented reality and virtual reality for delivery of information, instructions and training was highly "Desirable".

*3.2.1.6. System security and data management.* In this category participants showed strong concerns about data security from

**Table 2**
User requirements survey results for the Organisational Level.

| Organisational Level Requirements for Assembly Systems of the Future | | | | | |
|---|---|---|---|---|---|
| "Assembly work systems in the future should have…" | ES | DE | UN | NA | OA |
| Functions that are able to change their behaviour autonomously to accommodate new products and production processes | 48% | 46% | 6% | 0% | 94% |
| The ability to easily reconfigure the workplace when introducing a new automated system or robotics (e.g. plug & produce capabilities) | 66% | 30% | 4% | 0% | 96% |
| The ability to optimise by themselves to reduce the need for human intervention and adjustment | 36% | 54% | 8% | 2% | 90% |
| The ability to reconfigure themselves to increase efficiency and minimise effort and increase efficiency when changing production processes | 26% | 66% | 4% | 4% | 92% |
| Continuous data collection for analysis of system performance and optimisation needs | 66% | 34% | 0% | 0% | 100% |
| Self-adjusting capabilities to cope with changing needs of workforces and different worker capabilities | 38% | 56% | 6% | 0% | 94% |
| The ability to self-adjust to compensate for lower training and experience levels | 28% | 50% | 22% | 0% | 78% |
| The ability to self-adjust to compensate for reduced technical capabilities (older computer programs) | 24% | 52% | 20% | 4% | 76% |
| On-the-job work instructions that guide the worker through assembly or support processes (i.e. inspection, routine maintenance) to reduce the need for organised off-the-job training and supervision | 66% | 34% | 2% | 0% | 98% |
| Capabilities included in the automated system or robot that take advantage of the available workers expertise/knowledge | 44% | 44% | 12% | 0% | 88% |
| Continuous interaction all systems in the organisation for resource allocation | 48% | 44% | 8% | 0% | 92% |
| Direct connection to organisational systems for post-production product service and support | 38% | 48% | 14% | 0% | 86% |
| Constant recording of tool usage data to a central system to improve maintenance activities | 54% | 44% | 2% | 0% | 98% |
| Constant recording of automation/robot usage data to a central system to manage maintenance activities | 48% | 50% | 2% | 0% | 98% |
| Monitoring work station performance for future process improvement | 52% | 44% | 4% | 0% | 96% |
| Constant logging of production waste data for the purposes of future planning | 36% | 52% | 12% | 0% | 88% |
| Direct connection to internal control systems (e.g. Enterprise Resource Planning, Manufacturing execution systems, etc.) to adapt the assembly process | 58% | 38% | 4% | 0% | 96% |
| The ability to evaluate optimal levels of automation for workers (i.e. from fully automated to fully manual through collaborative) | 28% | 66% | 8% | 0% | 92% |
| Abilities for determining optimal levels of automation to meet economic requirements | 32% | 56% | 10% | 2% | 88% |
| Capabilities for evaluating workers' levels of satisfaction of and identify potential workplace improvements | 44% | 48% | 6% | 2% | 92% |

**Table 3**
User requirements survey results for Automation and Robotics.

| AUTOMATION AND ROBOTICS | | | | | |
|---|---|---|---|---|---|
| "Assembly work systems in the future should have…" | ES | DE | UN | NA | OA |
| Automation/robotics that are controllable by the operators working in the system | 60% | 36% | 2% | 2% | 96% |
| Automation/robotics that can only be adapted by management | 10% | 28% | 60% | 2% | 38% |
| Automation/robotics that can change themselves safely to meet varying production demands | 40% | 56% | 4% | 2% | 94% |
| Automation/robotics that can change safely on their own to meet different environmental conditions like varying light and noise levels | 34% | 52% | 10% | 4% | 86% |
| Automation/robotics that can change safely by themselves to meet different physical capabilities of the involved operators, such as size differences | 54% | 40% | 4% | 2% | 94% |
| Automation/robotics that can change safely on their own to meet different experience capabilities of the involved operators | 32% | 56% | 10% | 2% | 88% |
| Automation/robotics that run at a constant rate or on a constant programme and do not change | 12% | 26% | 60% | 2% | 38% |
| Automated/robotic functions that will adapt to suit each operator's preferred working methods | 12% | 74% | 12% | 2% | 86% |
| Automation/robots that can adapt its speed to correspond with an operator's profile (i.e. expertise, skills, capabilities, preferences, trust level) | 42% | 48% | 8% | 2% | 90% |
| Robots that work collaboratively and safely with an operator on shared tasks in fenceless environments | 62% | 34% | 2% | 2% | 96% |
| Safety mechanisms that make operators comfortable when collaborating with automation/robots during assembly | 84% | 14% | 0% | 2% | 98% |
| Robots have safety capabilities that immediately stop the robot in the event of an accidental collision | 86% | 8% | 2% | 4% | 94% |
| Robots have safety capabilities that move the robot away from the worker in the event of an accidental collision | 74% | 20% | 6% | 2% | 92% |
| Safety capabilities that adapt the speed of the robot according to the distance or speed of the operator | 74% | 20% | 4% | 2% | 94% |
| Functionalities to adapt the safety strategy based on the operators preferences and what is happening in the area surrounding the robot | 30% | 50% | 18% | 2% | 80% |
| Safety capabilities that differentiate between people and other kinds of potential obstacles, and adapt the automation/robots behaviour to suit | 50% | 46% | 2% | 2% | 96% |
| The ability to make operators aware of whether or not the safety mechanisms and devices are functioning effectively | 66% | 32% | 0% | 2% | 98% |
| Robots should work safely alongside or near to an operator but on separate tasks | 28% | 30% | 40% | 2% | 58% |
| Automation/robotics that can self-adapt its configuration to an operator's physical characteristics (i.e. height, arm length) to avoid potential ergonomic issues | 48% | 48% | 2% | 2% | 96% |
| Robots that do not work with or in close proximity to humans | 16% | 14% | 70% | 4% | 29% |
| Robots that notify management about the completion and the status of the task | 36% | 46% | 16% | 2% | 82% |

**Table 4**
User requirements survey results for Communication and Interaction Mechanisms.

| COMMUNICATION AND INTERACTION MECHANISMS | | | | | |
|---|---|---|---|---|---|
| "Assembly work systems in the future should have…" | ES | DE | UN | NA | OA |
| A workstation PC with an interactive computer system that allows the operator to interact and control the automation/robot/system | 56% | 28% | 16% | 0% | 84% |
| Automation/robot/systems that can be controlled with a computer system on a mobile devise (e.g. tablet, smartphone) | 30% | 64% | 6% | 0% | 94% |
| Operators interacting non-verbally with automation/robot/system by using handheld controls, or an emergency stop button | 54% | 36% | 10% | 2% | 88% |
| Automation/robot/systems that operators interact with using gestures | 16% | 54% | 30% | 0% | 70% |
| Automation/robot/systems that operators interact with using pre-defined voice commands | 20% | 60% | 20% | 0% | 80% |
| Automation/robot/systems that operators interact with using natural speaking (i.e. non-predefined commands) | 8% | 68% | 24% | 0% | 76% |
| Automation/robot/systems that operators can choose based on their preferences or capabilities to interact verbally and/or non-verbally with the automation/robot/system | 28% | 46% | 26% | 0% | 74% |
| The automation/robot/system has feedback abilities to show that it has understood a command | 56% | 36% | 8% | 0% | 92% |
| The automation/robot/system uses sound or voice message to provide feedback and notifications to workers | 28% | 54% | 18% | 0% | 82% |
| The automation/robot/system has visual capabilities (e.g. computer systems, lights, projected messages, etc.) to display relevant feedback and notifications to operators | 40% | 60% | 0% | 0% | 100% |
| The automation/robot/system has both visual and auditory capabilities to present relevant feedback and notifications | 30% | 66% | 4% | 0% | 96% |

external threats, and about protection and management of operators' personal data in their "Essential" ratings (Table 7). This trend was echoed in qualitative comments where participants suggested that operators should be able to access their information and that strong data protection rules should be applied.

In summary, the user level requirements survey has demonstrated support for the development of adaptive, flexible and self-optimising assembly systems of the future to meet both production and operator changes and differences, and the use of novel technologies, although participants are from a limited demographic sample.

#### 3.2.2. High level requirements results

The relevance of current standards to the technology categories identified above was reviewed and those deemed most relevant are shown in Table 8.[1] As we have focused on European standards these are covered by EN and ISO standards with the exception of the British BS 8611 due to it being a unique but highly relevant new standard for this project and user-centred system design.

## 4. Business cases requirements analysis

In addition to the benchmarking and requirements capture studies, further requirements for new assembly systems were extracted from the four different A4BLUE use case scenario business cases.

### 4.1. Method

Four business cases were analysed to accord with the two industrial use cases from the aerospace manufacturing sector (AIRBUS and CESA) and two laboratory based use cases, one of which is developed within an industrial research organisation (IK4-TEKNIKER), and the other within an academic institution representing the automotive sector (RWTH). To capture the business case requirements information was sought from the use case (UC) partners to define their main motivations, challenges and ideal future situation. At a later stage of the project the use cases will be used for analysis to verify the requirements

[1] Sources of standards: International (ISO) standards: https://www.iso.org/standards.html; European (EN) standards: https://www.cen.eu/work/products/ENs/Pages/default.aspx; British standards (BS): https://shop.bsigroup.com/.

**Table 5**
User requirements survey results for System Feedback and Assistance.

| SYSTEM FEEDBACK AND ASSISTANCE | | | | | |
|---|---|---|---|---|---|
| "Assembly work systems in the future should have…" | ES | DE | UN | NA | OA |
| System feedback that keeps the operator aware of their own work progress | 44% | 48% | 8% | 0% | 92% |
| Process analysis and feedback that can be accessed when requested by operators, such as productivity and performance information | 42% | 46% | 12% | 0% | 88% |
| Automatic and continuous analysis of work as it is completed and feedback mechanisms | 36% | 54% | 8% | 2% | 90% |
| The ability to recognise an operators capability and provides personalised assistance | 24% | 66% | 10% | 0% | 90% |
| An ability to detect when technical assistance is needed by an operator | 22% | 72% | 4% | 2% | 94% |
| Functionality for providing the assistance that operators can request and/or select | 34% | 60% | 4% | 2% | 94% |
| The ability to provide personalised assistance to meet the individual needs of an operator | 24% | 62% | 14% | 0% | 86% |
| Ergonomic assessment capabilities so that it can provide postural guidance to operators | 40% | 40% | 20% | 0% | 80% |
| Ergonomic assessment of physical capabilities of the operator to provide assistance | 40% | 42% | 16% | 2% | 82% |
| Assistance and feedback that is designed to keep operators satisfied as they work | 32% | 52% | 16% | 0% | 84% |
| All tools and equipment for assembly always available to operators | 50% | 28% | 22% | 2% | 76% |
| Tools/equipment that are provided to operators at specific stages of assembly when they are needed | 56% | 40% | 2% | 2% | 96% |
| Knowledge capture/capitalization systems for process improvement | 36% | 60% | 4% | 0% | 96% |
| System optimisation proposal taken from feedback | 28% | 62% | 10% | 0% | 90% |
| Augmented reality devices (e.g. Google glasses) to provide remote assistance from qualified personnel to operators | 12% | 76% | 12% | 2% | 86% |
| Automated systems that suggest how to manage emergency and/or unexpected situations | 42% | 54% | 4% | 0% | 96% |
| An off-the-job system that uses virtual reality simulation to train operators to do tasks by reproducing it in a virtual world | 24% | 54% | 22% | 0% | 78% |

framework described in Section 2.

### 4.2. Results

Results consist of summaries of the business case context information supplied by the use case partners, specifically the description of the context, the main challenges and then the main objectives.

#### 4.2.1. Industrial use case: AIRBUS

*4.2.1.1. Context.* The AIRBUS business case scenario is based on complex hydraulic system assembly within the landing gear nose box of aircraft. The manual assembly task currently requires paper-based instructions comprising various sets of operations and numerous parts to be installed in awkward positions. The main operations involved in the assembly process are: pre-installing & pre-tightening marking, screwing, tightening, crimping, protection sealant and varnish applying, glue applying, cleansing, metallization. For this use case scenario smart tools and AR devices are the primary technologies being considered.

*4.2.1.2. Main challenges.* In this hydraulic system assembly scenario, the standard operating instructions are currently paper based and not adapted to the worker profile and context. Assembly tools are manual and do not reflect specific operation unit and related parameters. Also, the availability of accurate information for quality inspectors is not reliable and not full traceable.

*4.2.1.3. Main objectives.* (1) Synchronise information automatically among different types of resources (Human and/or Machine), (2) evaluate and measure the impact of adaptable AR in terms of assembly performance and error; (3) support the automatic adaptation of the parameters of tools involved in the assembly process; (4) introduce on demand Standard Operating Instructions (SOI) to improve the traceability and the quality assurance of integration with the shop floor control system.

#### 4.2.2. Industrial use case: CESA

*4.2.2.1. Context.* The CESA use case will concern the assembly of the retraction actuator for a single aisle aircraft main landing gear and includes two application scenarios: the assembly process itself and an essential deburring operation that is performed completely manually to guarantee a smooth assembly process (to remove burs generated during the machining process).

*4.2.2.2. Main challenges.* Deburring application scenario: (1) high variability of the process, quality problems and reduced productivity due to dependence on manual works; (2) safety risks from metal chips of the deburring operation; (3) potential ergonomics issues as well as ambient ones due to a long exposition to noise during the deburring operation; (4) long, repetitive and motivating operation.

Assembly application scenario: (1) complex and time-consuming information retrieval (e.g. technical instruction, control instruction, drawings, etc.) not adapted to the worker or context (e.g. ongoing operation); (2) lack of off-job/on-job training capabilities to support

**Table 6**
User requirements survey results for System Information and Instructions.

| SYSTEM INFORMATION AND INSTRUCTIONS | | | | | |
|---|---|---|---|---|---|
| "Assembly work systems in the future should have…" | ES | DE | UN | NA | OA |
| Virtual reality that provides off–the-job training to operators | 26% | 56% | 20% | 0% | 80% |
| Augmented reality that provides information and instructions to operators while they are working | 36% | 56% | 10% | 0% | 90% |
| The capability to display work procedures that show how to do tasks using multimedia capabilities (text, pictures, images, videos) | 50% | 52% | 0% | 0% | 100% |
| The ability to verify each step of the proposed procedure and display the information related to the next step | 40% | 58% | 2% | 0% | 98% |
| Capabilities to allow operators to interrogate information/instructions further | 46% | 54% | 0% | 0% | 100% |
| Mechanisms for operators to directly input their own recommendations for work instructions, information updates or working conditions | 32% | 64% | 8% | 0% | 92% |
| Mechanisms for operators to directly input multimedia content (i.e. including photos, videos, and voice) into the process information and instructions | 24% | 62% | 14% | 0% | 86% |
| Functions that track operators' activity and/or work performance and inform them of recommendations and remedial actions | 20% | 60% | 18% | 2% | 80% |
| Information presented on demand using a wireless augmented reality device | 24% | 58% | 18% | 0% | 82% |
| Capabilities that allow operators to exchange best practices/problem solving solutions with other operators in the process instructions | 32% | 58% | 10% | 0% | 90% |

**Table 7**
User requirements survey results for System Security and Data Management.

| SYSTEM SECURITY AND DATA MANAGEMENT | | | | | |
|---|---|---|---|---|---|
| "Assembly work systems in the future should have…" | ES | DE | UN | NA | OA |
| Only allow personnel who work on maintaining and overseeing the information technology systems to have access to an operator's data | 30% | 30% | 38% | 2% | 60% |
| Allow personnel who work on information technology systems AND managers to have access to the operator's data | 20% | 38% | 40% | 2% | 58% |
| Allow information technology personnel and managers to have access to system data (e.g. data on process, data on the systems performance) | 58% | 28% | 14% | 0% | 86% |
| Let anyone have access to an operator's data | 2% | 4% | 94% | 0% | 6% |
| Let anyone have access to system data | 6% | 10% | 84% | 0% | 16% |
| Destroy an operator's data 5 years after they have left their company of employment | 26% | 44% | 28% | 2% | 70% |
| Retain an operator's data indefinitely | 2% | 22% | 76% | 0% | 24% |
| Retain system data indefinitely | 20% | 30% | 50% | 0% | 50% |
| Only hold data for specific operators at specific workstations | 2% | 46% | 52% | 0% | 48% |
| Capture all data about operators' working activities | 10% | 38% | 50% | 2% | 48% |
| Only capture specific data about the operator (e.g. the height they set the workbench to) | 22% | 44% | 30% | 6% | 65% |
| Comprise IT security mechanisms that will prevent attacks from external sources | 84% | 14% | 2% | 0% | 98% |

**Table 8**
Selected relevant standards.

| European Machinery Directive | Automation and Robotics | Ergonomics & Human Factors | Digital Systems |
|---|---|---|---|
| EN ISO 12100:2010 | EN ISO 10218-1:2011 | EN ISO 9241-100:2010 | ISO/IEC TR 29194:2015 |
| ISO 13849-1:2015 | ISO/TS 15066:2016 | EN ISO 9241-110:2006 | ISO/IEC 24779-1:2016 |
| IEC 60204-1: 2016 | BS 8611:2016 | EN ISO 9241-129:2010 | EN 62264-1:2013 |
| EN 614-2:2000 | | EN ISO 9241-161:2016 | EN 62541 |
| EN ISO 11161:2007 | | EN ISO 9241-210:2010 | EN 62714-1:2014 |
| EN 842:1996 + A1:2008 | | EN ISO 9241-303:2011 | |
| EN 981:1996 + A1:2008 | | EN ISO 9241-400:2007 | |
| EN 894-1:1997 + A1:2008 | | EN ISO 9241-410:2008 | |
| EN 894-2:1997 + A1:2008 | | EN ISO 9241-920:2009 | |
| EN 894-3:2000 + A1:2008 | | EN ISO 6385:2016 | |
| EN 894-4:2010 | | EN 10075-1-2000 | |
| EN 1005-2:2003 + A1:2008 | | EN ISO 14915-1:2002 | |
| EN 1005-3:2002 + A1:2008 | | | |
| EN 1005-4:2005 + A1:2008 | | | |
| EN ISO 14738:2008 | | | |

workers certifications (i.e. workers must be certified for each concrete process, and re-certification must be performed periodically); (3) lack of collaborative tools allowing experienced workers to share information, knowledge and lessons learned with young or less-experienced workers.

*4.2.2.3. Main objectives*. Deburring application scenario: introduction of a robot to cooperate with the operator in the deburring operation to reduce process variability, improve ergonomic and safety conditions and increase productivity and quality.

Assembly application scenario: (1) provide all the information required to perform the specific ongoing operation; (2) include on the job, AR based training capabilities that can adapt to worker profiles, adapt training and provide technical instructions to reduce the duration of the operator training and the whole assembly process; (3) incorporate knowledge management capabilities to allow workers to share information, tips, expertise; (4) display all information in a single and easy-to-use interface.

### 4.2.3. Laboratory use case: IK4-TEKNIKER

*4.2.3.1. Context*. IK4-TEKNIKER facilities already contain a pilot scenario in its shop floor lab that is used for research and experimentation purposes to advance in collaborative robotics. The target business use case is the collaborative assembly of an aircraft latch valve in a fenceless environment and it involves two application scenarios: (1) the collaborative assembly itself including auxiliary activities as initial preparation activities and final inspection; (2) the transport of the completed part to the warehouse.

*4.2.3.2. Main challenges*. Collaborative assembly application scenario: (1) the robot's behaviour does not adapt to an operator's profile (e.g. anthropometric characteristics); (2) the workplace does not support multimodal interaction to support different worker capabilities (e.g. expertise level, skills) or potential disabilities; (3) the technical specifications are paper based and follow a common format independently of the worker profile and no specific on-the-job guidance is provided based on the ongoing operation; (4) the safety mechanisms in place are not able to distinguish the nature of the obstacle or predict the intentions of mobile obstacles to adapt the robot's behaviour.

Logistics application scenario: the transportation of the finalised part to the warehouse is performed manually by the assembly operator and it is a time consuming, non-added value operation.

*4.2.3.3. Main objectives*. Collaborative assembly application scenario: (1) boost adaptation to human variability by reducing work requirements (in terms of physical characteristics, capabilities or skills to perform the activity) and workers' physical/mental workload through automatic mechanisms including adaptation capabilities, personalised assistance and multimodal interaction capabilities; (2) enhance close cooperation between human and robots, by rising safety (and trust) in shared workplaces with industrial robot without fences through the introduction of new safety measures and provision of appropriate feedback to the workers; (3) increase process reconfigurability and flexibility by easing the integration of new hardware (e.g. robots) and software components; (4) provide on-the-job guidance.

Logistics application scenario: integrate an autonomous mobile robot to cover auxiliary logistics activities by collecting parts from the collaborative work cell and transporting them to the warehouse once

the parts have been assembled and inspected.

#### 4.2.4. Laboratory use case: RWTH

*4.2.4.1. Context.* The RWTH Aachen University use case concerns production of electric vehicles, which is characterised by low production volumes, a high number of variants and by frequent product ramp-ups. Accompanied by increasing market dynamics and demand volatilities, system flexibility requirements are continuously rising. Thus, the target business case is the final assembly of electric vehicles, mainly focusing on the main assembly operations handling, adjusting and joining as well as on the auxiliary processes of picking, documentation and information provision. Furthermore, it involves the provision of the required tools by means of an automated interactive tool trolley. Two applications are developed in the Ramp-Up Factory Aachen at RWTH Aachen University: (1) assembly of the rear light and brake pedal as well as (2) mobile tooling supply.

*4.2.4.2. Main challenges.* Rear light and brake pedal assembly: (1) information delivered by technical instructions does not consider workers' experience and skills; (2) training times for new workers are high; (3) product variants lead to errors picking the right part; (4) difficulties in the adjustment of the rear light to the correct position; (5) decision on automating specific tasks.

Mobile tooling supply: (1) process efficiency is being compromised by workers using idiosyncratic methods to retrieve tools; (2) current ergonomic problem of tool trolley pushing; (3) operators require support to find required tools and avoid errors; (4) worker acceptance of new solutions is uncertain.

*4.2.4.3. Main objectives.* Rear light and brake pedal assembly: (1) improve worker satisfaction by providing information based on individual experience, skills and personal preferences; (2) reduce training times for new employees as well as during launch of new products and product variants; (3) improve process efficiency by reducing errors in picking of variant parts, tools and connecting elements through interacting information provision systems; (4) connect stakeholders and operators in production to further strengthen the continuous improvement process by deriving valuable process and quality data with little effort.

Mobile tooling supply: (1) improve process efficiency by eliminating variability in worker methods to retrieve tools; (2) improve ergonomics and efficiency in the tool provision process; (3) support the worker to find the required tool to avoid errors; (4) implement and validate a method and relevant software to determine the optimal degree of automation within production that workers will accept.

### 4.3. Results summary

Based on the qualitative information collected about the use case scenarios that is described above, Table 9 below summarises the key business case requirements.

## 5. Conclusions

The three component studies in this investigation constitute a substantial body of work that employed different methodological approaches to capture key information from a range of sources. This ensured breadth and depth of information, and although the studies were independent of one another, the complementarity of their results provides an indication that they are valid findings. Together, the benchmarking analysis for adaptive assembly systems, the multidimensional user requirements survey, and the business case requirements analysis are separate preliminary steps towards a common goal: to produce enhanced socio-technical assembly systems that incorporate advanced technologies to augment human-system interaction and performance measures, worker satisfaction and socio-economic sustainability. As this

**Table 9**
Summary of business cases requirements.

| | UC1: AIRBUS | UC2: CESA | UC3: TEK | UC4: RWTH |
|---|---|---|---|---|
| Organisational level requirements | Assess worker satisfaction<br>Online monitoring of relevant KPIs | Assess worker satisfaction<br>Online monitoring of relevant KPIs | Assess worker satisfaction<br>Online monitoring of relevant KPIs | Flexible configuration by defining the optimal level of automation<br>Assess worker satisfaction<br>Online monitoring of relevant KPIs |
| Automation and robotics | Smarts tools | Robot co-operating in the deburring process | Dual arm robot collaborating in assembly<br>Autonomous mobile robot for internal logistics | Mobile tool trolley |
| Communication and interaction mechanisms | GUI user interface based interaction | GUI user interface based interaction | Verbal and non-verbal interaction with cobot (gestures, voice)<br>Active safety mechanisms | Verbal and non-verbal interaction with tool trolley (gestures, voice) |
| System feedback and assistance | On the job guidance adapted to worker and operation through AR<br>Smart tool automatic calibration<br>Information adaptation to operator needs and skills | Information adaptation to operator needs and skills | Ergonomic (anthropometric adaptation) | Tools/ equipment always available to operators<br>Information adaptation to operator needs and skills |
| System information and instructions | Training through AR and VR | Exchange of best practices and lessons learned through factory social network | AR to provide technical and inspection instructions | AR for picking and rear light positioning |

was essentially an exploratory study to gather early indications, its limited sample sizes and depth of data collection are a natural consequence. However, although these were separate small developmental studies, they are highly related and the results together form an early stage foundational body of knowledge to guide the rest of the project and enhance the design, application and acceptance of new systems. Moreover, the considerable alignment in the information that has been gathered from various sources which supports that identified requirements and trends are reliable and representative.

The benchmarking activity described in Section 2 involved a coupled literature review and stakeholder analysis. It was successful in the aim of generating more comprehensive and valid data than that of other models that are available in the literature but have not been derived from context-specific inquiry. This information can be expanded at a later stage of the project when the use case scenarios are evaluated with human participants as additional information or new factors may emerge as a result of further development of the demonstrators. The multilevel requirements analysis was similarly successful due to the adoption of a more structured and targeted approach to collecting data than appears to be typical in the literature. The combination of high level and user level data clearly provides a more comprehensive and valid framework, combining formal specifications with subjective opinion. The business case analysis also provided a detailed and customised evaluation of the use case scenarios that would not be found in any other available model of findings. This enabled the project to design demonstrators that include and test relevant technologies to improve our knowledge of human-system interaction and design requirements.

Limitations of the study concern maturity of the research and breadth/depth of current data. Firstly, it was very appropriate for these three component studies to be conducted at the beginning of the project to gather initial indications from key stakeholders and existing literature. However, in subsequent stages of the research these pieces of work will need to be updated as technology development, industrial conditions – and potentially people's opinions – advance. For this reason, the literature and high level requirements documents will be monitored and updated throughout the project to incorporate any emergent or changing requirements. Second, the participant samples in both surveys (benchmarking and user requirements) were limited to contacts of the consortium and therefore a broader sample size and multiplicity would be advantageous. As the survey designs are intentionally simple it will be possible to conduct wider cross-cultural, cross-sector, and cross-disciplinary surveys later in the project to gather richer and more statistically useful/reliable data. Moreover, this will enable the survey to be administered to individuals who are not stakeholders and therefore reduces bias. Most of the further work will involve operators as end-users in much more depth which will boost validity. Thus, the approaches already applied and described in this paper will form the basis of further research work in the project.

The A4BLUE project is continuing to develop its use case demonstrators using these findings. Further work will involve the design and development of the adaptive system architecture, including the virtualisation of workplace related assets, integration with automation mechanisms and legacy systems, adaptation management, multi-modal interaction mechanisms, assistance tools such as VR and AR based training and guidance, collaborative knowledge management, development of a method of usability assessment, and integration of a model of satisfaction for the determination of the optimal level of automation from a socio-economic perspective. Additionally, at a later stage of the project when the use cases are at a more mature or complete stage of development, it is intended that further analysis will be undertaken to verify that the requirements identified in this investigation are appropriate. If these requirements are supported their collation to form a 'requirements framework' will be justified to provide a practical design aid.

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# Adaptive automation assembly: Identifying system requirements for technical efficiency and worker satisfaction

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