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A framework to design a human-centred adaptive manufacturing system for aging workers

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Abstract

The so-called smart manufacturing systems (SMS) combine smart manufacturing technologies, cyber-physical infrastructures, and data control to realize predictive and adaptive behaviours. In this context, industrial research focused mainly on improving the manufacturing system performance, almost neglecting human factors (HF) and their relation to the production systems. However, in order to create an effective smart factory context, human performance should be included to drive smart system adaptation in efficient and effective way, also by exploiting the linkages between tangible and intangible entities offered by Industry 4.0. Furthermore, modern companies are facing another interesting trend: aging workers. The age of workers is generally growing up and, consequently, the percentage of working 45–64 years old population with different needs, capabilities, and reactions, is increasing. This research focuses on the design of human-centred adaptive manufacturing systems (AMS) for the modern companies, where aging workers are more and more common. In particular, it defines a methodology to design AMS able to adapt to the aging workers' needs considering their reduced workability, due to both physical and cognitive functional decrease, with the final aim to improve the human-machine interaction and the workers' wellbeing. The paper finally presents an industrial case study focusing on the woodworking sector, where an existing machine has been re-designed to define a new human-centred AMS. The new machine has been engineered and prototyped by adopting cyber-physical systems (CPS) and pervasive technologies to smartly adapt the machine behaviour to the working conditions and the specific workers' skills, tasks, and cognitive-physical abilities, with the final aim to support aging workers. The achieved benefits were expressed in terms of system usability, focusing on human-interaction quality.

1 Introduction

In the context of Industry 4.0, manufacturing has to be smart and adaptive thanks to collaborative and flexible systems able to autonomously solve the problems arising during the process [26]. For this purpose, increasing attention has been recently paid to pervasive and smart decision support systems able to optimize machines' features and behaviours according to collected data, current conditions and process requirements. To face this highly complex scenario, the Industry 4.0 initiative has been launched in Germany and is actually strongly promoted by the European strategic programs due to its potential to change the European economy via cyber-physical systems (CPS) [27]. In this scenario, major approaches for increasing production changeability and flexible control are based on reconfigurable systems able to cope with unpredictable situations and dynamic production scenarios [30]. Cyber-physical systems (CPS) can be used to bring machine autonomous control, have self-adaptive behaviours and intelligently react to specific conditions. Current smart manufacturing implementations are mostly at the plant and production level, and use information technology, sensor networks, computerized controls, and production management software to improve process efficiency as a key performance objective [46]. However, such adaptivity is oriented so far to mostly optimize the production system efficiency in term of time, costs and production rates, while human factors (HF) have not been included in such scenario. It means that even in smart factories human beings (i.e., workers, operators, technicians) has to operate in a new manner, with the support of enhanced information sources available in modern industries.

The attention to human factors in industry is an emerging trend, and represents a relevant topic also for advanced engineering informatics applications. Starting from the extraction of human-based knowledge to create intelligent computer integrated manufacturing systems [63], to the analysis of both physical ergonomics and human cognition to develop smart production environments [59,60].

Today, the Industry 4.0 framework has the potential to include also humans into its highly innovative processes, and in particular aging workers that have specific needs and abilities. This is a crucial aspect for modern companies since the demographic changes as well as national regulations for late retirement, and a greater health that allow people to work for a longer period, are responsible for a sensible increase of the workers' age [33]. In this context, adaptive manufacturing systems (AMS) can successfully be a part of modern production systems to support workers in everyday jobs thanks to adaptive behaviours according to the occurring events as well as the human actions and capabilities.

Human-centred design is becoming crucial in manufacturing system design due to two main factors: the increasing age of workers as a consequence of global population aging, and the growing complexity of systems that are hard to manage and maintain. Indeed, it is widely recognized that the average age of world population is growing, as a global and continuous trend, affecting humans in general and thus also people working in manufacturing contexts [48]. Numerous studies claim that in 2050 around half of workers will be aged over 50 in developed countries, and the presence of older workers in production and operative roles will have an impact on economic growth and manufacturing efficiency [1,17]. As far as the impact of such a trend on companies, studies about aging workers demonstrated that the functional capacities, mainly physical, show a declining trend after the age of 30 years, and the trend can become critical after the next 15–20 years, so that from 45 to 64 years old there is a significant decrease of their capacities, both physical and cognitive ones. Such loss is about 20–25% in respect to the full capacity considered at 30 year old, and it affect both workers involved in physically demanding jobs and mentally demanding positions. Therefore, the age of 45–50 years have often been used as the base criterion to refer to "aging worker" [32]. The "early" definition of aging among workers from the occupational health point of view is due to possibilities for preventive measures: preserving their health and wellbeing is fundamental to maintain their ability longer and better. This is particularly important in the actual era characterized by a participation rate of workers who are aged 45–50 years or older in modern companies processes. Contemporarily, machines are becoming more and more digitalized and technologically advanced, thus they require to workers higher mental abilities, which inevitably decrease with age [42]. In this context, considering HF in system design is fundamental to properly handle with system complexity and make also complex system easy to control, manage and maintain. Problems referred to aging workers (45–64 years old), most of which related to consequences of the aging process as well as to changes in the working conditions and methods, and new demands on workers (e.g., higher flexibility, extended knowledge, polyvalence) have been documented on industrial cases in Europe [62]. In the Industry 4.0 framework, a lot of information can be available to properly manage the human-machine interaction by properly controlling the adaptive behaviours of both machines and interfaces, supporting the above-mentioned problems referred to aging workers. For these purposes, having systematic approaches to bring intelligence into the shop floor is required to provide factories with flexible and adaptive behaviours able to effectively face different working conditions and avoid downtime, delays and production rate decrease. In this context, the present research proposes an approach to design a human-centred AMS based on the flexible adaptation of the machine and interface according to the workers' needs and capabilities. The paper presents the human-centred design approach adopted to correlate workers' needs and system features at different levels (considering the users, the context, the machine, and the interface) and to test the designed adaptability on virtual prototypes. For this purpose, in particular, it is based on virtual commissioning (VC) approach to model and simulate the smart system and define the most proper adaptive behaviours, and implements case-based reasoning (CBR) algorithms to realize the human-centred adaptive behaviours according to the working conditions, process data, and workers' tasks as well as physical and cognitive abilities. System variables, related to the process, the machines and the workers, are monitored by AMS sensors and connected to the simulated system (i.e., virtual prototype) as well as the control system by CPS. The system is context-aware and is able to change its behaviour according to the defined adaptive rules. As a result, both machines and interfaces can adapt their behaviour according to the process parameters, monitored in real time, as well as to the requirements of the specific user interacting with the system. The industrial case study focused on the re-design an existing machine tool by adopting the proposed approach. Firstly, the human-related problems were analysed and a set of control system parameters were identified. Then, the machine was equipped with sensors and feedback devices to monitor the most critical tasks, and a virtual simulation system has been created to simulate the real process and to define possible adaptive behaviours of the system, by testing also the effect on virtual prototypes. Finally, a system prototype has been developed and tested with users to prove the improved human performance by experimental usability testing, thanks to the new AMS.

Section 2 presents the research background and motivation; Section 3 describes the research approach; Section 4 presents the industrial case study; Section 5 contains concluding remarks and future works.

2 Research background

2.1 Collaborative and smart manufacturing systems

Modern industrial systems are asked to adapt to constantly changing market requirements by maintaining the global competitiveness of manufacturing companies [29]. In this context, smart manufacturing systems (SMS) focus on the integration of interconnected systems into manufacturing industry thanks to the creation of linkages between tangible product-process assets (called also "physics-ends") and cyber-decision support assets (called also "cyber-ends") in production, logistics and services, with the final scope is to provide self-aware and self-adapting systems able to intelligently adjust the production patterns [13]. Physics-ends are, for instance, machines, materials, tools, while cyber-ends are data collection and storage tools, data processing systems, monitoring devices, and any other items that create a digital "twin" on the physics items[3]. Among SMS, the so-called reconfigurable manufacturing systems (RMS) and flexible manufacturing systems (FMS) can be included. Indeed, both of them exploit the linkages between their real assets and the virtual ones (emulated) to predict the system behaviour and to adapt its actions and

reactions in a flexible way. The main differences between FMS and RMS refer to the systems' flexibility and scalability concerning the production capacity; in particular, FMS refer to a generic system flexibility [9], while RMS usually address on-demand customized flexibility through scalability to incrementally realize different functionalities and capacities [16]. The concept of SMS is more recent but, in a certain sense, includes the previous ones. It refers to a fully integrated, collaborative manufacturing system that responds in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs, thanks to the new smart technologies and information and communication systems [46]. With respect to RMS and FMS, a SMS is characterized by the capacity to integrate data and information from multiple applications as well as smart products or sensors about the manufacturing context, which can be composed to form new solutions represented by a single machine, an entire factory or a network of companies. The link between interconnected computer systems and physical items has been defined as CPS [35]. CPS allows managing such interconnected systems to enhance physical assets with computational capabilities; a comprehensive overview has been recently provided by [64]. In different ways, this merger of physical and virtual worlds opens up new areas of innovation that will optimize the entire manufacturing industry to create higher quality products, improve productivity, increase energy efficiency, and sustain safer plant floors. Factories are becoming more and more connected and monitored by intelligent devices (i.e. sensors, data acquisition systems, computer networks and cloud computing). On one side, this trend is preparing the right infrastructure for designing and implementing a CPS-based factory. On the other side, the introduction of sensors and control systems are generating a huge quantity of data, which is called Big Data, available to be further processed for other scopes [18]. Lee et al. presented the main differences between today's manufacturing factories and an Industry 4.0 factory considering three levels: components, machines, and production systems [36]. One of the most interesting applications of CPSs in manufacturing is the creation of advanced control systems for intelligent factory automation, where CPSs allow retrieving process data in real time and correlating them with computational systems and simulation models for further analysis, which can be oriented to create efficient production and factory control system. Numerous advanced approaches for factory control and industrial automation systems have been proposed (from model-based control techniques to intelligent control techniques, event-triggered and self-triggered control, until discrete event and hybrid control techniques) as discussed by [61].

Diversely, the term AMS usually refers to machines and production systems, which are defined "adaptive" to underline the attention on human actions and specific users' needs, diversely from the reconfigurable manufacturing systems (RMS) that focus on quickly adjusting their production capacity mainly for production planning purposes [16]. In this context, AMSs can be regarded as complex systems able to continuously monitor values and trends of external environment or internal variables, optimizing their goals according to certain reaction rules, and adapting their behaviour to accomplish their goals [6]. Whereas RMSs are more focused on production planning issues, AMS are more oriented to the machine functions with regard to the expected outputs and the human actions, to adapt their own behaviour to the occurring events and working conditions. They are based not on reconfiguration, but proper adaptation. Sophisticated control logics are required to support system adaptation, which may range from real-time parameter adaptation to structural adaptations thanks to advanced control algorithms, estimation of not directly measurable parameters, planning of set of smart sensors, formalization and knowledge-based modelling of processes and forecasting of variables. AMSs accomplish enhanced adaptability to changeable environments through increased sensing capabilities of the factory system to realize intelligent and adaptive behaviours. The term "adaptation" comprises a wide spectrum of characteristics [4]. The term "adaptivity" is a property expressing a self-adaptation, that is realized when a certain system or interface can modify or control itself with the aim of getting matched to changing circumstances, requirements or needs. "Self-adaptation" is an intrinsic process going on inside the interface or system automatically, resulting in step-by-step or continuous conversion or modification of the system properties. About interfaces in particular, adaptivity means to adjust the forms of information transfer, transform the information content, alter or merge modes of information flow, exchange or combine communication media. In mechatronics, the goal is to apply the adaptivity concept to both machines and interfaces. Indeed, ASM generally also include smart Human-Machine Interfaces (HMI) as the first communication channel between humans and machines [5]. The interface serves as a bridge between humans and mechatronic systems and, by their functions, they allow a proper information exchange: as a consequence, the HMI adaptation allows matching different or changing requirements and automatically adapting to dynamic circumstances in order to create dynamic and context-aware interfaces [58]. In this sense, interface adaptation is fundamental to have a good system performance since the relation between humans and automation is critical and difficult to predict and control [49]. In order to be adaptive, the interface has to reconfigure its main elements: (1) layout (colours, fonts, and graphical compositions in general); (2) contents (information and data provided and managed at different levels of detail); and (3) feedback (interaction way to provide alerts and notifications). A good classification of adaptive patterns and a deep analysis of adaptation mechanisms have been provided by [45]. Several approaches have been proposed in literature for AMS: from online parameter adaptation [65] to structural adaptation [7,10]. All approaches achieve adaptive features by the formalization and modelling of process knowledge based in order to forecast the machine control variables, based on the creation of a knowledge base where processes are mathematically modelled in their detailed behaviours and the related parameters are sensed. In order to predict the adaptive system behaviours and design optimized adaptive control strategies, Pellicciari et al. proposed to use virtual commissioning (VC) for AMS design and engineer [50]. VC makes use of full virtual simulation of machinery or hardware in the loop simulations to validate systems at different levels (plant, cell, machine or single operations) by reducing the commissioning time and improving the software quality [55]. In this context, Lee et al. defined a CPS-based architecture for adaptive manufacturing systems based on a "cyber-twin" for each factory machine to keep track of changes during the process [35]. About adaptive machine tools in particular, previous studies in literature mainly focus on machine-machine communication and optimization of the process parameters (i.e., time, speed, vibration, cost, etc.) [28,8] without including the human dimension. Table 1 summarizes the main features of the so-called intelligent manufacturing systems (mainly RMS, FMS, AMS and SMS).

Table 1 Comparison among the different types of intelligent manufacturing systems.

Main reference	[9]	[16]	[13]	[52]

Systems	Flexible manufacturing systems (FMS)	Reconfigurable manufacturing systems (RMS)	Smart manufacturing systems (SMS)	Adaptive manufacturing systems (AMS)
Main objective	To address on-demand flexible production processes	To address on-demand customized and highly variable production processes	To provide self-aware and self-adapting systems able to intelligently adjust the production patterns	To adapt the entire production system, including machines, material flows, controlling system and human beings, to new condition in an efficient, fast and integrated way
Adopted strategy	Ability to change the order of operations executed on a part, and to use multiple machines to perform the same operation on a part to absorb large-scale changes (volume, capacity or capability)	Machine scalability to incrementally realize different functionalities and capacities	Linkages between tangible product-process assets ("physics-ends") and cyber decision support assets ("cyber-ends") in production, logistics and services	Increased sensing capabilities of the factory system to realize intelligent and adaptive behaviours, thanks to combination of real-time parameter adaptation, advanced control algorithms, knowledge-based modelling of processes, estimation of not directly measurable parameters and forecasting of variables
Difference with previous systems	Capacity to respond in real time to meet changing demands and conditions in the factory	Higher efficiency due to an accurate system reconfiguration to meet changing conditions, considering the factory, the supply network, and the market needs	Capacity to integrate data and information from multiple applications, sensors, and smart products (a single machine, an entire factory or a network of companies)	Self-adaptation of machines, interfaces and production planning by the optimization of both system performance and human-machine interaction

In the context of AMS, the review of the state of the art showed that CPS can be usefully applied to observe the behaviours of physics-ends (i.e., products, machines, interfaces, etc.) and to learn the patterns of various working regimes for different types of machines in order to define adaptive algorithms and provide self-configurability. However, none of the approaches proposed until now consider include human-related data and HF analysis in AMS development.

2.2 Human-centred manufacturing for aging workers

One of the key issues in designing complex systems including human interaction consists of understanding the relationship between system features and human actions and reactions [56]. Considering manufacturing systems, it means that system design has to consider the users' needs and hopefully customizes the system features to meet individual requirements and support subjective conditions. The starting point is to understand how people work, which are their needs, and how they should work in an ergonomic way; the final goal is supporting the workers to be a part of the final systems to achieve the higher performance. The concept of human-centred manufacturing [57] places human characters, skills, creativity and potentiality at the centre of the activities of technological systems, and focuses not only on how humans interact with technology, but also questioning how and why technology may be of service in supporting human work [23]. The power of such idea, when it was conceived in 1990s, was limited mainly to the technological constraints: difficult human action monitoring, generally too intrusive and expensive for industrial applications; limits in technology miniaturization, which obstacles an effective integration into machines; problems to manage data in real time and share with "smart" application. Nowadays, we have two important changes that push towards human-centred manufacturing: great technological advances that make available a variety of smart devices for industrial application at low cost, and the phenomenon of aging workers that requires more supportive and assistive production systems. Since the actual manufacturing scenario is characterized by aging workforce, age-related problems in machine system design should be naturally considered in machine design and adaptation.

In fact, aging workers is a worldwide phenomenon. In Europe, by 2040 the proportion of the younger age group (15–24 years) in the total working-age population will have decreased by 5%, compared with 1990, while the proportion of those aged 55–64 years will have increased by almost 6% [17]. By the year 2025, it has been estimated that the proportion of working individuals over the age of 50 years will be 32% in Europe, 30% in North America, 21% in Asia, and 17% in Latin America. Italy in particular is among the first countries in the world for life expectancy, but not for life expectancy in good health [20]. As a consequence, aging workers are numerous and they are frequently affected by age-related problems.

About human factors, functional capacities (both physical and cognitive) show a declining trend after the age of 30 years, and it can become critical after the next 15–20 years if the demands of work do not decline [32]. Therefore, anyone in 30–64 years of age could be considered an aging worker. However, the definition of an "aging worker" is generally based on the period when major changes occur in relevant work related functions during the course of work life, in the range of 45–64 years old: so that, 45 years is considered the beginning of the physical and cognitive "decline" [11]. Starting from 45 years old, age-related problems progressively occur, even if there are great differences among different people, according to their level of training and health as well as their own lifestyle, and the peak of work-related stress is about 50–55 years old [24]. Age-related problems in manufacturing industry mainly consist of slower learning and training, lack of flexibility or adaptation to new technology and equipment, low productivity in fixed time span, problems to endure shift-work, and high rate of sick leave [62]. In order to prevent troubles for workers, the physical and cognitive workload of jobs should be decreased with advancing age; workers should be trained to have regular exercises to keep the cardio-respiratory and motor capacity, and machine should reduce the work demands by supporting workers in an active way [32].

The natural decrease of the physical and cognitive capabilities can be classified into different classes: decrease of visual ability, decrease of acoustic ability, decrease of musculoskeletal force, decrease of motion capabilities, decrease of memory and concentration, problems of balance and thermoregulation [22]. Such decreases imply a lower "resilience" to job workload over the years. The concept of "resilience" is taken from cognitive psychology and refers to the "person's capacity to respond to pressure and the demands of daily life" [38,39]. Dictionary definitions include concepts like flexibility suppleness, durability, strength, speed of recovery and buoyancy. In short, resilience affects the human ability to "bounce back". Resilience at work is recognized as a defining characteristic of employees who deal well with the stresses and strains of the modern workplace. In this perspective, eye problems that can highly affect performances when high reactivity is required or hard working conditions obstacle the use of glasses, reduced mobility or reduced ability to lift weights, memory reduction or anxiety that can seriously decrease attention and reactivity in stressing conditions are seen as factors reducing the workers' resilience.

Actually the analysis of HF in industry, and in particular in manufacturing, mainly focuses on the analysis of physical ergonomics in order to avoid work-related musculoskeletal disorders (WMSDs) due to awkward postures and repetitive actions. The sequence of actions carried out by workers and the postures assumed during task execution can be evaluated by empirical methodologies for risk assessment, including NIOSH [14], RULA [41], OCRA [47], or the more recent WERA [53]. Such analyses focus on anthropometric information modelling, task analysis, and physical workload assessment. However, modern technology-oriented sectors require also the investigation of human interaction and the assessment of the cognitive workload, and the concept of "resilience" should be introduced.

Nowadays, thanks to the recent advent of control technologies and CPSs in industry, the development of smart systems for manufacturing is facilitating the creation of human-centred systems. Furthermore, the demonstrated impact of HF on manufacturing productivity and production cost [40,25,43] are pushing both companies and society to promote human-centred intelligent systems to support the workers' tasks and to improve the production quality. In this context, AMS should look to both technological issuers, and human-centred principles, due to the high influence on manufacturing process quality. Indeed, although modern manufacturing processes are extremely automated, human-machine interaction plays in important role since interaction is more and more complex and ways of interactions are changing to achieve short cycles and customized goods. Furthermore, interfaces have to consequently manage a huge quantity of information also being connected to servers and cloud resources. Such factors could represent a barrier for older people, acting as inhibitors to usage rather than facilitators as they are generally not familiar with those tools, do not have an appropriate background and are not accepted [15]. The lack of attention to the human-related issues in system adaptation is creating a lot of problems in system usability and, finally, in production quality performance [43]: the main motivation of the proposed paper starts from these evidences and aims at working in such poorly explored area. Especially within manufacturing environments, a human-centred approach is essential to enable workers to face the growing complexity of modern manufacturing systems, which require high-precision movements and reactive cognitive abilities, and to improve their natural "resilience".

3 Research approach

3.1 General approach for AMS

The research proposes a human-centred approach to design and engineer AMS based on correlation matrices for requirements' elicitation [12], Case-Based Reasoning (CBR) algorithms to build up adaptive behaviours [31], and Virtual Commissioning (VC) to simulate and optimize the adaptive system control [55]. Such an approach supports designers in AMS definition and implementation.

The adaptation is based on providing support to aging workers (mainly 45–64 years old). System adaptation is defined from the analysis of the workers' resilience and "functional decreases", which affect their natural capacity to cope with job demands so reduce their resilience at work, considering also the workers' age and skills. Subsequently it considers also external factors like the working environment, the machine features and the user interface features. Correlation matrices are used to correlate the system design components, related to the machine and the interface, with the workers' needs and the environment (i.e., context), as demonstrated also by [37]: in particular, matrices allow structuring the problem variables into a rigorous way and defining how they affect each other. In this way a reference model for adaptation is created for the machine control. In respect with Lee et al. [37], the present research extends the analysis domain and includes also the analysis of HF, the operational context and external conditions as important system variables. Furthermore, the specific worker's physical and cognitive abilities are related to individual conditions (i.e., age, gender, education) and the specific manufacturing scenario (i.e., role, tasks, responsibilities). A library of possible problems and solving behaviours is created by exports in machine design and HF, and CBR algorithms support the creation of system adaptation strategies based on the comparison between past cases and new cases, and on dependencies and similarities within past cases. A set of CBR algorithms is defined for adapting a past case solution to a new case solution based on the determination of intervals of variations for the attributes of the new case, as suggested by [21]. It allows creating a set of adaptive system behaviours. Finally, VC is used to provide an interdisciplinary simulation environment where the gap between mechanical and control engineering activities can be filled and where their synergic actions can be numerically evaluated on simulated effects [2]. VC allows setting up system behavioural models on which basis realistic simulations are created to virtually explore the existing machine behaviour and test new solutions during the design stage. Behavioural simulation integrates mechatronic aspects with mechanical machine features and interface behaviours to evaluate the actual performance of difference system configurations and validate a huge number of system design variants. For this reason VC represents a strategic advantage in validating and selecting solutions really actionable with robust mechatronic solutions according to production constraints (e.g., time, sequence of actions, etc.).

Such an approach allows obtaining a context-aware human-centred adaptive system by mapping the problem domain and fostering the fulfilment of the heterogeneous constraints of the specific problem (i.e., a certain static

behaviour). Then, VC simulation allows creating the system knowledge base according to the actual system behaviours and identifying the process weaknesses, which represent the opportunities for creating the adaptive behaviour rules. CBR algorithms are used to model a set of solution variants starting from the present case exploiting the system knowledge previously defined, in order to define the rules for context-aware adaptation. Finally, the new design variants are simulated and evaluated by the virtual model and the best adaptive solution is defined on the basis of the system performances achievable.

About problem domain mapping, correlation is set into a 4D space, considering the four "dimensions" characterizing the human-machine interaction: *worker*, *machine*, *interface* and *context*. The machine dimension is considered when machine adaptivity has to be defined, while the interface dimension is considered when the interface adaptivity has to be defined. In each triad, three dimensions are correlated each other by a double entry matrix. Furthermore, each dimension is in turn related to sub-dimensions: for instance, the *worker* dimension is characterized by the relation between *functional decreases* (according to different categories), *skill*, *age*; the *context* dimension, related to the environment, is defined by specific *manufacturing operations* (or stages), occurring *events* (or conditions), and *tasks* to be performed by both the machine and the user; the *interface* dimension is characterized by the *graphics and layout*, the *dynamics and semantics*, and the *content* to be provided; finally the *machine* dimension is characterized by *monitoring system data*, the *actuation system actions*, and the *control system information*. The combination of the four dimensions results into a set of context-aware adaptation algorithms that guide respectively the machine and the interface to adapt its behaviours and features in a dynamic and interactive way according to the context and the workers' needs. Thanks to a set of correlation matrices, the logical relations among the considered dimensions can be mapped and easily investigated.

As far as workers' mapping, four classes of "functional decreases" affecting the worker resilience are defined on the basis of literature review [22] as described in Table 2:

(1) visual decrease affecting the human sight,

(2) auditory decrease affecting hearing,

(3) motor decrease affecting motor skills, and

(4) cognitive decrease affecting memory and cognitive faculties.

Table 2 Work-related functional decreases considered in the research.

	Functional decreases (affecting the workers' resilience)			
Classes	Visual	Auditory	Motor	Cognitive
Categories	Long-sightedness	Minor hearing loss (26–40 dB)	Minor reduced mobility of legs	Anxiety disorders
	Short-sightedness	Medium hearing loss (41–55 dB)	Medium-high reduced mobility of legs	Memory problems
	Far-sightedness & Astigmatism	Medium-high hearing loss (56–70 dB)	Minor reduced weight lift (<25 kg)	Difficulties in concentrating and processing large amounts of information
	Contrast Sensitivity	High hearing loss (71–90 dB)	Medium reduced weight lift (<15 kg)	
	Colour-blindness	Sever hearing loss (>90 dB)	Highly reduced weight lift (<6 kg)	

Such decreases represent the main causes of loss of resilience at work [32,33,62]. About skills and age, 5-class categories are identified (from 1 to 5). As far as context features, classification refers to the specific manufacturing company or to the acknowledged practice in the industrial sector of interest. About system features, the model refers to [50]. About interface features, the model considers the main features of Graphic User Interfaces (GUI) for web applications according to [37].

3.2 Design methodology for AMS

A systematic methodology is defined to formalize the logical correlations depicted in the previous section with the final aim to define adaptive system behaviours taking into account the human-related needs. The method overview is presented in Fig. 1 and can be synthesized in five main steps as follows.
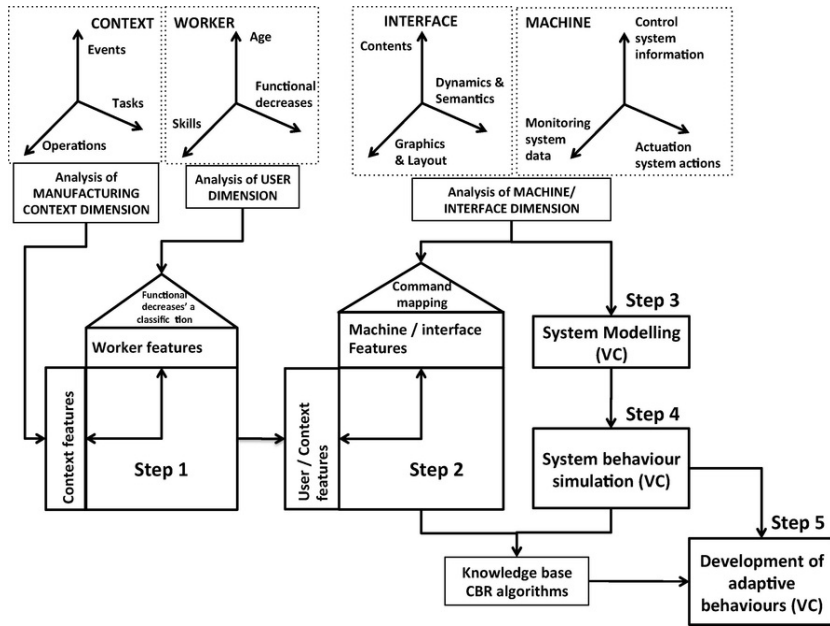
Fig. 1 Human-centred methodology to design an AMS.

Step 1. Mapping between worker and context dimensions. firstly, conditions and needs of the specific worker are considered in terms of skills, age and functional decrease to finally obtain a comprehensive description of the specific workers' features and capabilities according to the proposed schema (Section 3.1). In this context, the classification of functional decreases proposed in Table 2 is adopted. Usually, all involved workers are classified at the beginning of the adaptation process and data are collected into a system database, properly encrypted, and retrieved when needed by personal identification devices (e.g., RFID, finger-scan, eye-scan) already used in industry. After that, the specific manufacturing context, in terms of machine modelling, conditions classifications, and tasks to be executed by both machine and users are defined and organized according to the proposed model (Section 3.1). Data about machine static features are collected into a system machine database, while CPSs connected to the machine provide information about dynamic data and specific operating conditions. Static data refers the machine features such as its maximum capacity, its power, its workspace, its precision and accuracy, etc. (not-changeable), while dynamic data refers to context-related data such as the machine energy consumption, the spindle speed, the vibrations, the generated noises, etc. (changeable according to the specific context, user or occurring event). Finally a matrix relates the manufacturing *context* dimension and the *worker* dimension, so that the specific worker's features are correlated with the context variables. Correlation is expressed by experts in HF and manufacturing ergonomics by heuristic evaluation [44]. A 0-3-9 point scale is used as suggested by studies in usability and quality functional deployment (QFD) areas [12]. Such correlations describe, for instance, how the execution of each specific task is affected by the worker's resilience, which consider eventual losses due to functional decreases, personal skills, or external events that affect task execution. Using a 0-3-9 scale (where 0 means no correlation, 3 mean slight correlation, and 9 means strong correlation), the relations among the items are emphasized. As a result, a *worker/context* matrix is defined.

Step 2. Mapping between the machine/interface matrix and worker/context matrix. similarly to step 1, both machine and interface are analysed and described by means of their features, according to the proposed schema (Section 3.1). A first matrix relates the specific machine features with the interface command definition, to link machine capabilities with the corresponding interface features. In particular, the machine behaviour is modelled according to data, actions and information to be processed, while the interface is decomposed into its features like graphics and layout, dynamics and semantics and contents. As a result, a *machine/interface* matrix is defined. Subsequently, a second matrix relates the *worker/context* matrix (defined in step 1) with the *machine/interface* matrix. Correlation is carried out by experts in manufacturing system modelling and cognitive ergonomics, and expressed by heuristic evaluation according to 0-3-9 point scale, as before. Such correlation describes, for instance, how the user has to act to activate a certain process, how the interface shows process information, etc. It maps how the user conditions and the context-based events affect the working condition of the machine as well as the interface features. Also in this case, the adoption of a 0-3-9 scale emphasizes the relations among the interested items.

Step 3. System modelling. thanks to a VC tool, the system as described in the previous steps (comprehending user, manufacturing context, machine and interface) is modelled and reproduced by a virtual prototype. Thanks to a VC tool, mechanical 3D CAD models of the manufacturing system, together with system kinematical properties and related physical behaviours, are developed and inserted into the virtual environment. Subsequently, CAD models are

connected with the real control system and the related control logics to create mechatronic virtual prototypes, replicating the complex behaviour of the mechatronic systems: the system model includes the controller, the related control logics, tasks definition, sensors description, input/output data, actuators descriptions, and the HMI. Interface is modelled both in its graphical and logical parts. The final model is a real "smart object" where mechanical, electronic and software behaviours are coupled.

Step 4. System behaviour simulation. the system model developed in step 3 is programmed with specific control logics and connected with input/output ports for VC simulation. Simulation is powerful to execute behaviours and create the system knowledge base considering all the system features into an integrated simulation environment. Simulation refers to both process execution and human-machine interaction. The process is tested totally on virtual prototypes by a set of program logics; while the human-machine interaction is tested using virtual prototypes into an immersive virtual environment, exploiting Virtual Reality Lab facilities. In such context, the system interface as well as the machine behaviours and process performances are simulated in a highly realistic manner and the worker directly experience the virtual scene by navigating the environment in a realistic way. Simulation involves usually two different kinds of users: experts and trainees. Expert users are workers, involved in the production companies and trained to handle with virtual prototypes, while trainees are researcher working with simulation tools but they don't have a former knowledge about the specific machine and the production context. Thanks to the immersive simulation environment, workers can express a judgement about system usability. Involvement of both researchers and former workers is useful to collect different feedback and define the system improvement. Furthermore, the virtual simulation offers the possibility to explored, analysed, and optimized numerous solutions and behaviours. In particular, system weaknesses in term of process execution and human-machine interaction are identified. Experts' feedback usually focuses on system usability issues and time performance, while trainees' feedback allows proposing novel solutions to improve human interaction, ergonomics and cognitive workload.

Step 5. Development of system adaptive behaviours. the weaknesses identified in step 4 are considered as critical points to be optimized by adaptive behaviours. For this purpose, CBR algorithms are adopted to the system knowledge base, previously defined thanks to simulation. Critical events and/or conditions are identified and a set of corrective rule and corresponding actions is developed and a wide library of adaptive behaviours is populated. Each corrective action is described by a workflow that can be executed automatically by the system virtual model and validate by continuous simulation: indeed, when a certain adaptive behaviour is executed, the virtual model generates some feedbacks from simulation, which can be used to verify if the solution is good or not considering all the constraints related to the user and the context as described above. Proceeding with iterative analysis, the best adaptive solution for each case is selected. The possible system configurations are filtered according to the required performances as well as the specific conditions about the environments, the machine and the human beings. Solution knowledge is structured according to CBR algorithms, and the most suitable solutions to face a certain situation are compared by a similarity measure based on the Minkowski formula [54]. The comparison between the current situation and a set of possible future solutions (as result of adaptation) allows also to retrieve their technical rules used to adapt the actual situation to the new one. As a result, a set of adaptive rule, actions and control algorithms is defined to properly control the machine and configure the interface features. In this way the optimized machine behaviour is intelligently determined according to the users and context conditions, while the user is supported in the execution of specific tasks by the adaptation of the interface features to his/her specific workability and external conditions.

Such a method is a step forwards the design of adaptive system in respect to a previous work focusing only on machine adaptation [50] and another work focusing on HMI configuration [51].

4 Industrial case study

4.1 Case study description

The industrial case study has been developed in collaboration with a large-sized Italian company producing woodworking machine tools. The woodworking sector has been chosen as it represents an interesting field of application. Indeed, such sector is living a rapid technological evolution: it currently represents a significant sector for Europe by providing jobs to about 2.3 million people in the EU28, it is a traditional sector where the technological complexity is growing fast, and the age of the workers is increasing due to the lack of new generations involved. Furthermore, Italy is the European country with the highest life expectancy and the higher rate of aging worker (over-45) involved in manufacturing [20]. In particular, over-55 workers are rapidly increasing in this sector (i.e., 9% in 2005, 25% in 2014) [19], and the authors monitored frequently age-related problems for workers acting on woodworking machine tools.

The case study focuses on the re-design of a woodworking NC processing centre, which is characterized by a close interaction with the operators to be controlled and managed. The final aim was to realize an adaptive, smart and collaborative manufacturing environment to support workers in their operation activities. In the case study, aging workers with 50–64 years old were considered. According to the specific analysed tasks, target users were both male workers (over-55) and female workers (over-50). Indeed, studies demonstrated how women show a particular functional decrease at 50–55 years old due to reduced muscular force and personal stress workload, which lead to a reduced workability [32]. Aging categories under investigation, in respect with the young workers, were proved to have a lower resilience to work due to both physical and cognitive functional decreases and must be assisted to achieve the best performance.

The case study is described in terms of:

- *Context:* machine tool control and basic operations for windows furniture production. The target machine is shown in Fig. 2;

- *Target users:* workers are usually grouped into 3 classes (Op1, Op2 and Op3), according to their capabilities and level of responsibilities. Op1 takes care about the load and unload of the machine, machine status monitoring and alert identification. Op2 is also able to accomplish some more difficult tasks like tool change, tool warehouse management, service groups control and maintenance (i.e. oil, compressed air, etc.). For the case study the target user was an aging Op1 worker (both male and female) in charge of basic machine control tasks. He/she had a medium-high age class (3), a medium level of education (3) and medium-high skills (4), he/she is long-sighted, and cannot handle more than 15 kg;

- *Human tasks:* tasks carried out by the machine operators mainly consist of machine loading and unloading, labelling of the machined "piece of wood", (hereafter wood part), monitoring of the working conditions, change tools when needed. The human tasks considered in the case study are listed in Table 2. Table 2 describes tasks referring to the three types of workers that can operate on the case study machines. Even thought results description focused on tasks carried out by Op1, all tasks are reported to provide a complete overview of the human-machine interaction complexity of the case study machine;

- *Environmental conditions:* a set of external conditions monitored by the embedded sensors and controlled by the control system were related to both the machine and the surrounding environment, as described in Table 3. They refer to the level of dusts, fumes, and external sound pressure for the environment, and to vibration, tool shape and geometry, and internal sound pressure for the machine. All the conditions were found to affect the humans' work in a significant way, due to direct impact on the workers' health conditions (i.e., fumes, dusts, sound pressure, vibrations) or the additional effort in machine operation (i.e., detecting a wrong tool change or control of the spindle vibration).

The general workflow representing the tasks considered in the case study is as follows:

(1) Material loading: the worker chooses the piece of wood according to the right geometry, typology and characteristics (i.e., code, weight, dimensions, etc.) and poses it on the loader. The system is already equipped with sensors to check the semi-finished wood part shape, weight and its geometrical profile. If the semi-finished part is correct, the machine automatically load the piece, otherwise it stops;

(2) Machining: the machine receives the material from the loader and moves it to the processing area where it is manufactured by the most appropriate tools, according to the machining working program. The process is completely automated, but the operator has to monitor the process to guarantee the require process quality;

(3) Operation monitoring: the worker monitors the machine functioning during the execution of the working program by the traditional machine PLC (with low usability features). The machine is already equipped with sensors to monitor machine parameters (i.e. spindle accelerations and vibrations, level of noise produced, level of dusts produced, shape of the piece of wood during working stages), but they are actually available as complex diagrams and statistics report, without influencing the machine functioning;

(4) Finished piece control: the machine verifies if the machined wood part is realized according to the technical specifications, by measuring its final shape and weight by cameras and sensors. The process is completely automatic;

(5) Material unload: when the finished wood part is properly manufactured, the machine moves the finished product to the unload area and the operator labels it in the proper way by sticking the proper label (generated by the system) and removes the part from the unloading area.

4.2 Design and prototype of the adaptive machine tool

The research focuses on the design of the new AMS. The design was carried out by adopting the proposed methodology, on the basis of the analysis of the existing system. The main criticalities of the existing machine were identified and analysed. Analyses involved experts from Academia and Industry working in the area of HF and system modelling, and was based on analysis of the human tasks by direct workers' observation. The main weaknesses of the original system were identified as follows:

- Limited support of human tasks offered by the user interface: the interface is complex and text-based, so it is difficult to read and requires the operator to spend time to interpret and understand the actions needed. The user interface also does not support the operator by indicating the next steps or, in case of stops, the fault in a clear way;

- Frequent musculoskeletal disorders (MSDs): the machine asks to product load and unload also when the operator is not able to do that job, and this fact causes disorders to operators, especially to the older ones (e.g. backache, neck and arm pains, etc.);

- Complex interface navigation: the user interface is difficult to navigate and information recovery is low and sometimes misleading, so some human errors usually occur;

- Difficult process monitoring: the machine offers data abut it functioning but there is a lack of consolidated and aggregated data view (i.e. graphs, diagrams, etc.) to be easily interpreted;

- Numerous stops and downtime: the machine is not able to react and adapt to changing conditions, so in case of not ideal condition, it stops and asks for the manual intervention or control;

- Stand-alone functioning: the machine works as a stand-alone system without considering the other machines in the same plant;

- Too large occupied area: the machine occupies a total area of about 100 square metres and additional space is required for part movements and accessory operations;

- Poorly comfortable workers positions: the workers have to assume discomfort positions and execute not ergonomic tasks, that can dangerously affect their physical workload (e.g., numerous lifting tasks, frequent trunk rotations, frequent stopping);

- Poor control and tracing of the worked part: the machine is not able to monitor the part along its production cycle, from the initial loading, during the operations, until the final artefact;

- Lack of information about the state of "health" of the machine and the surrounding environment: the machine does not inform the workers about their state of health and is not able to predict problems or to inform the workers in advance about possible troubles;

- Lack of awareness about the on-going process: the machine is not able to keep constantly inform the workers about the process advance in easy and intuitive way.

After that, the new system to be designed was firstly defined as composed by three main parts: the woodworking Machine Tool (MT), the Monitoring System composed by machine control devices and environmental sensors (MS), and the User Interface (UI) that is accessible by web-based and mobile devices. In particular, the new AMS was conceived considering that:

(1) the MT was re-designed and re-engineered with particular attention to HF and system usability (i.e., position of machine parts, simplification of workers' task, reduction of movements for task completion);

(2) a MS was introduced to collect useful data about the machine functioning and the workers' actions on it, which drive the system adaptability, in term of both machine and user interface, after a proper post-processing;

(3) the UI was re-design and enable with dynamic configuration properties according to the process needs and the specific worker's workability..

After that, the system was modelled in details and virtually prototyped using DELMIA V5's VC tool, thanks to its capacity to integrate different domains activities within a unique virtual environment. Then, the mechatronic virtual prototype of the complete system has been developed, connecting the real machine controller and HMI with a CAD-based simulation, which emulates the mechanical behaviour of the machine. For simulation, the effective machine conditions and behaviours were analysed from real cases and reproduced into the virtual environment. The I/Os and signals of the machine control system are interfaced with an OPC connection and a custom shared memory. In particular, VC simulation supported the creation of the system knowledge base to have a complete overview of all the monitored and controlled parameters. Furthermore, VC simulation allows verifying such a sequence of actions and identifying the most critical activities, especially those affecting the system usability and the user performance. The definition of the system weaknesses considered both the process and the user tasks, by directly involving users into realistic and immersive simulations. In particular, an immersive virtual reality environment was used to make the users interact with the virtual prototype like a real system. For these purposes, the ViP Lab facilities offered by the University of Modena and Reggio Emilia were used; it is equipped with a retro-projected large CADwall (6 × 2 metres), a 3D surround stereo system, and an infrared Vicon tracking system.

The definition of the existing system weaknesses was the starting point for the design of the new AMS: on the basis of the most critical tasks, the company and machine knowledge was studied and the MT, MS, UI and external influencing conditions were determined. For each condition, parameters about both user and environment were examined in order to define how they affect the critical tasks and how to improve the tasks' usability automatically, making the system adapt. Also data from the other machines in the same plant can be used.

On the basis of such weaknesses, an optimized machine and manufacturing workflow was defined. In particular, the new system has been conceived in order to minimize the occupied space and improve the system layout in order to optimize the material flows in the plant, to offer more comfortable working positions and improve ergonomics, to include a monitoring system able to check the quality of the manufactured part in different stages and to monitor the state of health of both machine and environment and inform the workers about its state in easy and intuitive way. Also a new system workflow was built considering an automatic detection of the specific user interacting with the machine and the external conditions. Adaptive rules are defined according to the proposed methodology on the basis of correlations between the machine/interface dimensions and the user/context dimensions. After that, a new workflow introduces a set of checkpoints where the system behaviours are adapted according to the specific users' characteristics as well as occurring conditions according to the adaptive rules. In order to realize the adaptive behaviours, the workflow supported also the definition of the new technology architecture by highlighting the necessity of proper sensors and system intelligence algorithms (e.g., when the users have to be avoided to lift a certain weight, the piece of wood has to be weights by sensors and the value corresponding to its weight compared with the specific users' threshold, properly collected into a database and recovered by a users' identification system). Finally, testing on the virtual prototype allowed system modelling and testing of the possible adaptive behaviours in advance on virtual manikins by using DHM tools, before the realization of the physical mock-up. Sample workers and experts from industry were involved in virtual immersive task simulation to verify the methods' matrices fulfilling, as proposed in Section 3.2.

Fig. 3 shows the conceptual architecture of the human-centred AMS, while the Fig. 4 shows an example of method's matrices, used to define the adaptive behaviours. Subsequently, such behaviours have been formalized into workflows, to point out the logical activity and data flows. It described how the proposed method support system configuration. In particular, it shows the correlation matrix between workers' functional decreases, as classified and presented in Table 2, and the workers' tasks, as described in Table 3, and the correlation matrix between tasks and user interface features, as described in Table 4. In particular, Table 5 shows an example of the interface features to be

configured and adapted. They were chosen in collaboration with the company project managers, on the basis of their experience and the feedback from the technical staff and the customer care staff. The interface was divided into sections and a set of features was defined and analysed in detail for each of them. Similarly, also the machine components were analysed and described by its main functions and input/output data to define their behaviours.
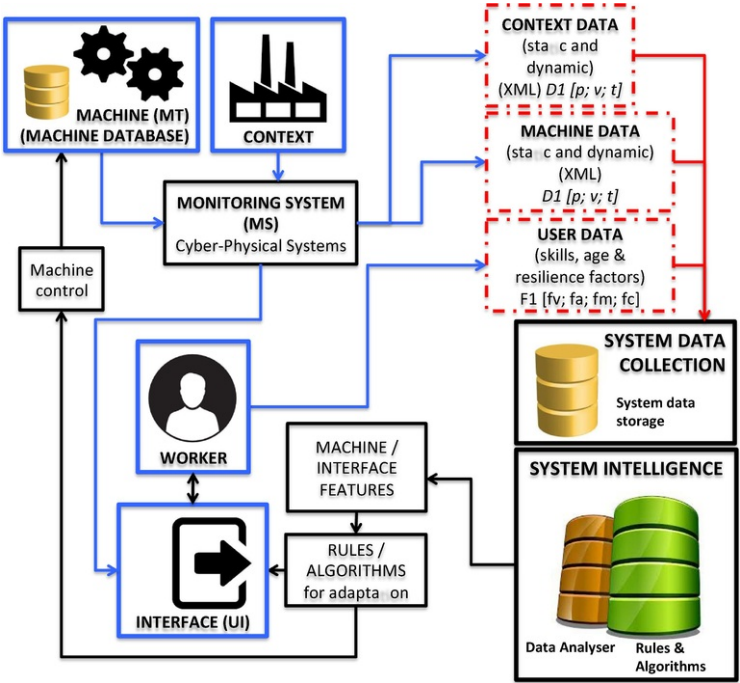

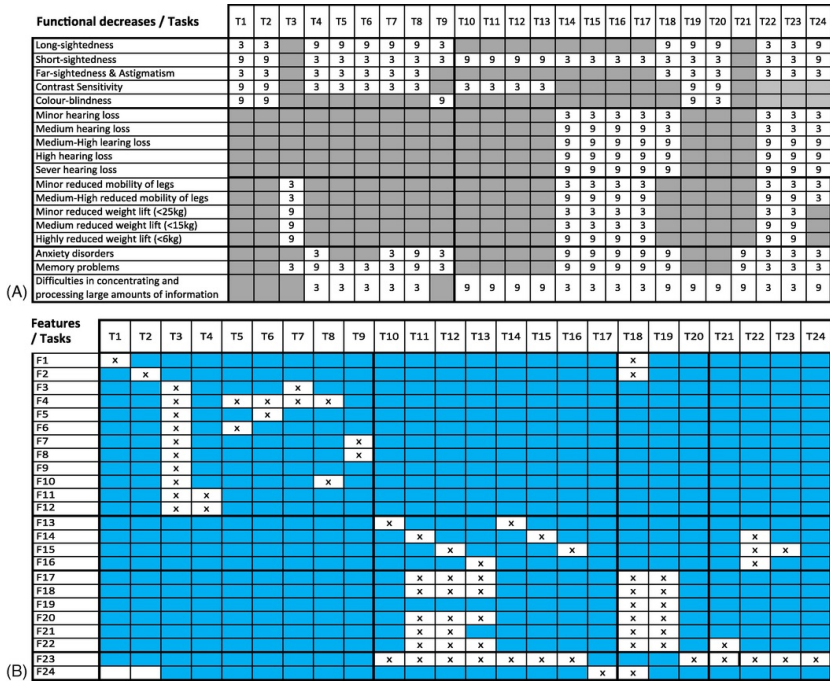**Fig. 3** Conceptual architecture of the human-centred AMS.

Fig. 4 Examples of correlation matrices used to define the AMS architecture and adaptation actions: correlation between workers' functional decreases and tasks (A) and between interface features and tasks (B).

(A)

Functional decreases / Tasks	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
Long-sightedness	3	3		9	9	9	9	9	3									9	9	9		3	3	9
Short-sightedness	9	9		3	3	3	3	3	3	9	9	9	9	3	3	3	3	3	3	3		3	3	9
Far-sightedness & Astigmatism	3	3		3	3	3	3	3										3	3	3		3	3	3
Contrast Sensitivity	9	9		3	3	3	3	3			3	3	3	3					9	9				
Colour-blindness	9	9							9										9	3				
Minor hearing loss														3	3	3	3	3				3	3	3
Medium hearing loss														9	9	9	9	3				3	3	3
Medium-High learing loss														9	9	9	9	9				9	9	9
High hearing loss														9	9	9	9	9				9	9	9
Sever hearing loss														9	9	9	9	9				9	9	9
Minor reduced mobility of legs				3										3	3	3	3					3	3	3
Medium-High reduced mobility of legs				3										9	9	9	9					9	9	3
Minor reduced weight lift (<25kg)					9									3	3	3	3					3	3	
Medium reduced weight lift (<15kg)					9									3	3	3	3					9	9	
Highly reduced weight lift (<6kg)					9									9	9	9	9					9	9	
Anxiety disorders				3			3	9	3					9	9	9	9	9	9		9	3	3	3
Memory problems				3	9	3	3	9	3					9	9	9	9	9	9		9	3	3	3
Difficulties in concentrating and processing large amounts of information				3	3	3	3	3		9	9	9	9	3	3	3	3	3	9	9	9	9	3	3	9

(B)

Features / Tasks	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	T21	T22	T23	T24
F1	x																	x						
F2		x																x						
F3			x			x																		
F4			x		x	x	x	x																
F5			x			x																		
F6			x		x																			
F7			x						x															
F8			x						x															
F9			x																					
F10			x				x																	
F11			x	x																				
F12			x	x																				
F13											x			x										
F14											x				x							x		
F15												x				x					x	x		
F16													x								x			
F17											x	x	x					x	x					
F18											x	x	x					x	x					
F19																		x	x					
F20											x	x	x					x	x					
F21											x	x						x	x					
F22											x	x	x					x	x		x			
F23										x	x	x	x	x	x	x				x	x	x	x	x
F24																	x	x						

Table 4 External conditions monitored for woodworking machines by the control system.

Context	Condition	Monitoring device	Collected data
Environment	Level of dusts	Dust sensors	16 bit data
	Level of fumes	Steams/fumes sensors	16 bit data
	Level of external sound pressure	Sound pressure sensors	dB data
Machine	Spindle vibrations	Accelerometers	0–1-2
	Tool shape and geometry	Cameras and vision system	0–1-2–3
	Level of internal sound pressure	Sound pressure sensors	dB data

Table 5 List of system interface features to be adapted in the case study.

Interface sections	Interface features
Header (common to all pages)	F1. Multicolour status bar for environmental parameters
	F2. Multicolour status bar for machine parameters
Load/Unload main page	F3. Loading minutes

	F4. Information about the part processed
	F5. Part volume
	F6. Part weight
	F7. Load button
	F8. Unload button
	F9. Information about parts that have been already loaded
	F10. Label to be put on the part processed
Detailed information page	F11. Information about parts to be loaded next
	F12. Information about running process
Video control panel page	F13. Video about manual lading information
	F14. Video about automatic lading information
	F15. Video about machine internal movements
	F16. Video about machine external locking clamps
Detailed diagram pages	F17. Diagram of dusts
	F18. Diagram of steams/fumes
	F19. Diagram of sound pressure
	F20. Diagram of vibrations
	F21. Diagram of internal noises
	F22. Combined graphs
Multi-level pages	F23. Multi-level information
Alert (common to all pages)	F24. Alert and warning messages

System adaptation is expressed by JECA (Justification-Event-Condition-Action) rules and CBR algorithms, based on finding solutions to unexpected events considering the solutions of similar past problems. The case study focused on human-machine interaction issues and considered the effect of the workers' workability, roles, environment and machines conditions (as described in Tables 2–4), on the interface features (Table 5) and machine main operations involved in the case study workflow (description in Section 4.1). A set of possible problems (more than 300) linked to the workers' behaviours was mapped and the most convenient solutions in terms of machine and interface adaptation were defined (about 160). If an expected event occurred, the system retrieved the expected solution and executed it. If an unexpected event occurred, the new event was judged by similarity index with past solutions, and the closest solution is run. If no one rule can be found inside the database, the exception is classified as unexpected and need to be solved with manual intervention, and the new created behaviour become a solution that will be added into the database as "past" cases after its execution. In order to recognize and classify the exceptions, a set of attributes has been defined to classify the type of exception itself (e.g., technical/technological, economical, temporal). The combination of features allowed the creation of appropriate events indexing used in rules definition and recognition. For every exception contained in the database, the attributes allow the retrieval of the relative JECA rule. The CBR mechanism is used for searching similar previous cases collected into a cases database, and for measuring the similarity between the current case features and the "past" cases. Solutions are then selected according to the similarity value, calculated by the Minkowski formula [54].

From the analysis of the correlation matrices populated for the use case, the main adaptation rules and system behaviours were defined. For instance, sighting problems affect many tasks due to difficulty in interface reading or

system signals' monitoring. As a consequence, adaptive rules were introduced able to resize the interface fonts or add acoustic cues to visual feedback to facilitate the user comprehension of the machine signals. Similarly, in case of hearing deficits of the specific user, acoustic signals were enforce by visual and haptic feedbacks. When memory or concentration problems occur in the specific user, the system interface supports the process control by informing the user on the next machine actions and on the aspects to be checked, exactly when he/she needs. In addition, the machine sensors allow automatically verifying some aspects that were originally checked by humans (e.g., correct profile of the wood part after loading and after the milling process, correct positioning of the wood part on the loader) while other automatic controls allows preventing human errors (e.g., control of the correct profile of the tool and its quality or control of the quality of the final product by image processing). The majority of the tasks were also simplified such as loading, labelling, or tooling change, to reduce both the physical and cognitive workload.

Fig. 5 shows the adaptivity management based on JECA rules retrieval or editing for respectively expected and unexpected cases. Fig. 6 synthetizes the workflow of original systems (A) and the new workflow realized by the new human-centred AMS (B). Their comparison describes how the human-centred system adaptivity is achieved (for brevity, not all the phases are reported, but only those ones with an relevant contribution to system adaptivity).
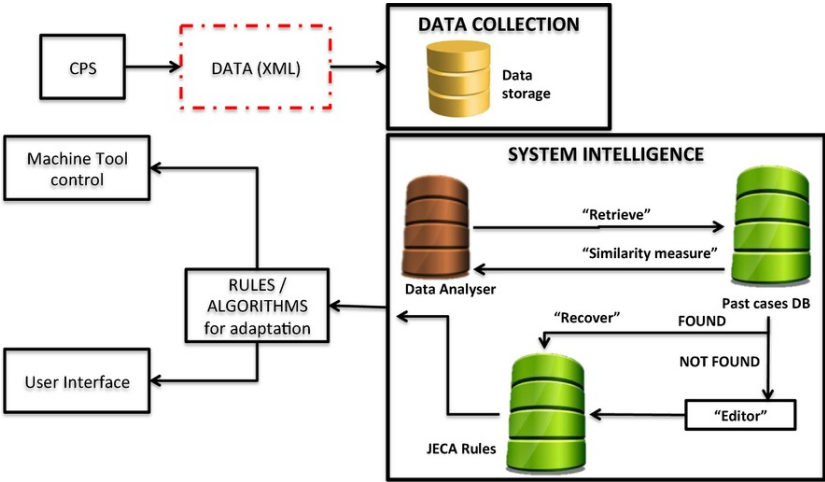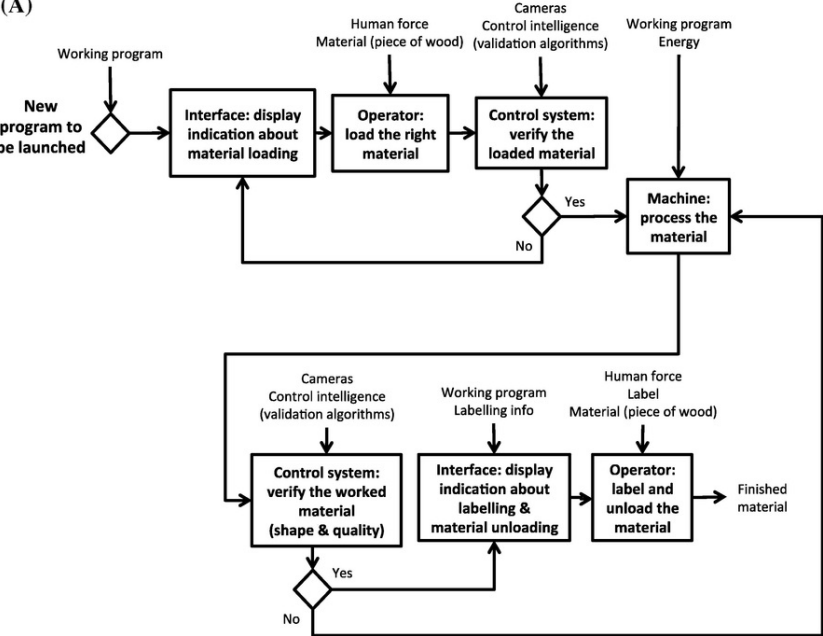

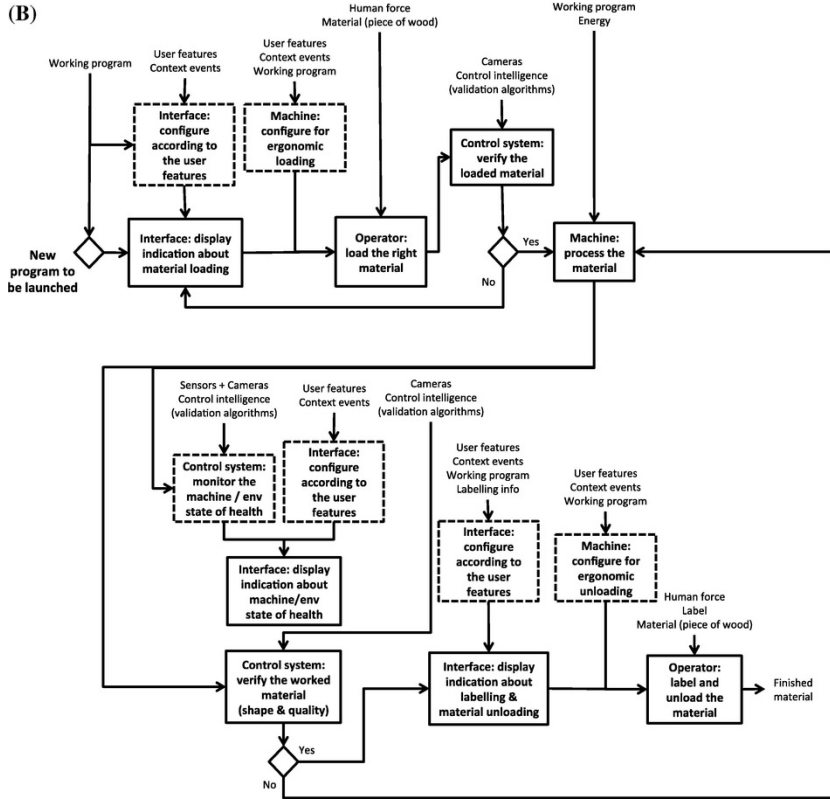**Fig. 5** Adaptation management schema according to the CBR approach.

(A)

Working program

New program to be launched

Human force
Material (piece of wood)

Cameras
Control intelligence
(validation algorithms)

Working program
Energy

Interface: display indication about material loading

Operator: load the right material

Control system: verify the loaded material

Yes

No

Machine: process the material

Cameras
Control intelligence
(validation algorithms)

Working program
Labelling info

Human force
Label
Material (piece of wood)

Control system: verify the worked material (shape & quality)

Interface: display indication about labelling & material unloading

Operator: label and unload the material

Finished material

Yes

No

Fig. 6 Simplified traditional manufacturing workflow (A) and the new AMS workflow (B).

The new system is adaptive, smart and collaborative. It is "adaptive" because it is able to react the specific users' needs and external conditions by changing its behaviours and features according to changeable dynamic situations; "smart" because it changes in a predicting way, since its change is base on real time data monitoring thanks to the integration of CPS; and finally "collaborative" because it supports users in their everyday work by offering ad-hoc features, but also considering what happen in the surrounding environment and into the other machines, connected according to the industry 4.0 paradigm, in a collaborative way.

As a result, the system is able to nearly realize a real-time adaptation, but it depends on the data network performance and the intrinsic latency of the connected systems.

4.3 Prototyping of the adaptive manufacturing system

After that, the preliminary prototype was realized to carry out usability tests with real workers in order to compare the usability of the new AMS with the previous machine. The system prototype integrates the MT with the system control and the MS focused on the MT loading-unloading area, the working area, and the tool storage area. Fig. 7 shows the prototypal AMS (A) and the VC simulation in Virtual Reality environment (B). By the simulation of the adaptive behaviours carried out during the design stage, a set of sensors to be included in the monitoring system (MS) has been defined. They allow monitoring the machine, environment, and human beings in an accurate way with respect to the tasks. The final MT is composed by the following sensors:

- Accelerometers to monitor the dynamic behaviours of the active components of the machine (i.e., spindles, roll bars, etc.) and detect part contacts and impacts eventually;
- Thermal probes to control the temperature of each single component and on the different working areas;
- Dust probes to monitor the level of dust generated and the consequently environmental sanitation of the different working areas;
- Microphones to monitor the general noise, internal and external to the working areas;

- Laser sensors and cameras to control the parts positioning (e.g., position of tools, loaded-unloaded piece of wood, generated scraps, etc.) by visual recognition and detection;

- RFID tags to identify the workers in order to make the system aware about the specific worker's abilities and needs.

(A)
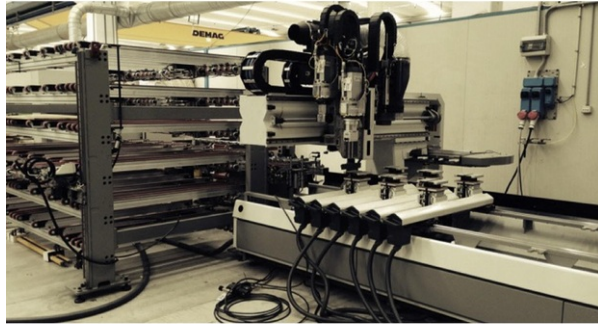
(B)

Fig. 7 The new AMS prototype (A) and the VC simulation in Virtual Reality environment (B).

The UI was available on the traditional PLC, but also on a specific mobile application accessed by smartphone and tablet. The interface was realized by adopting ASP.NET and Microsoft Ajax technologies. ASP.NET was used to create the main interface items and controls, while Ajax allowed managing the dynamic contents independently from the page structure and combining dynamic contents with standard controls easily. Such framework makes the interface accessible by different operating systems (i.e., Android, iOS, etc.).

The system sensors monitored the manufacturing process as well as the machine and environment state of health; the CPS as well as the PLC of the machine tool communicated with a server control system that collected and stored data into a common vault to create a dynamic system knowledge. In particular, data about human beings (i.e., name, role, positions, skills, behaviours, and functional decreases affecting workability) were stored into an encrypted database for privacy issues. Subsequently, the CBR-based system intelligence, included into the server control system, was used to process the occurring cases (i.e., specific machine behaviour, workers' tasks) and to control the system adaptation, both MT and UI, according to the user and the context needs, on the basis of JECA rules and similarity index to recover the best adaptive algorithms in order to react to the specific situation.

The new human-centred AMS is based on real time data collection and information processing to define the adaptive rules: data are collected by a central system, stored in a common vault, and then processed by proper system intelligence able to analyse the data and implement the correlations as described Section 3.2. After that, the adaptive logics and rules are executed and the system control is adjusted in real time to adapt the machine and the interface. As a result, the system defines a set of rules and algorithms to be used. Configuration rules are used to control both machine and interface and the adaptive behaviours are executed almost in real time. For these purposes, some additional actuators and sensors are introduced to make the machine move autonomously and check the position of some specific components (i.e., loader plane, product during the process, label, etc.).

An examples of an expected adaptive behaviour is as follows:

Worker data

ID: 0049463
Name: Mario Rossi
Role: Op1
Functional decreases: short-sighted, medium reduced-size weight lift (< 15kg)
Anthropometrical data: from specific 3D virtual manikin (percentile and nationality)
Machine data
Process status: material loading (waiting for semi-finished wood part)
Type of product to be machined: expected part geometry, weight, code, expected position in the machine
System monitoring
- Mario Rossi is tracked into the area and his position is checked according to the task
- Environmental data are monitored and check with respect to the threshold values
- Machine data are monitored and check with respect to the threshold values
System adaptation
MS: according to the Mario Rossi position, a safe area in created with MT and other devices cannot move
MT: the loading plane is put at the most comfortable height for Mario Rossi (inferred from anthropometrical data and real position), the system checks if the expected part weight can be handled by Mario Rossi (if yes, proceeds; if no, it generates an alarm and calls another workers available), the sensors check the wood part when it is loaded
UI: the interface in properly configured according to the task that Mario Rossi has to carry out in the specific process status, his role and his functional decreases affecting his workability (e.g., fonts are visualized bigger, contract is improved)

When an unexpected behaviour occurs, the system intelligence browses into the past cases without finding a similar solution and makes the system manager to define the new solution that will be added to the rule databases, to be used as a "past" case next times.

Thanks to such intelligence, MT and UI could adapt their behaviours according to the process requirements, the external conditions and the worker's workability. For instance, the system automatically recognized the dimensions of the semi-finished wood part on the loader in order to organize the following process steps, or move the tool in an easy-to-access position for tool change according to the specific worker's features (e.g., height, dominant hand, maximum force load, comfortable joint angles) and the machine status (i.e., needed inspections, state of health of mechatronic components). The IT system set-up of the AMS prototype is presented in Fig. 8. The system intelligence was located on the server and the communication with the MT controller as well as the UI application is managed by web services. The MT controller collects information about the machine, the process events, the workers, and the monitoring sensors. The UI application recognizes the specific worker (by RFID) and recovers information related to him/her directly from the server. When a task has to be executed on the UI, the UI application connects to the web server and the web service manages all the requests. CBR algorithms are applied at the server level, and the UI applications received elaborated information as answers to the web service. Interface reconfiguration is based on JECA rules, applied to the specific data about the worker, both general data collected into the system database and linked to his/her identification, and retrieved from his/her actions on the machine space, monitored to the monitoring systems.
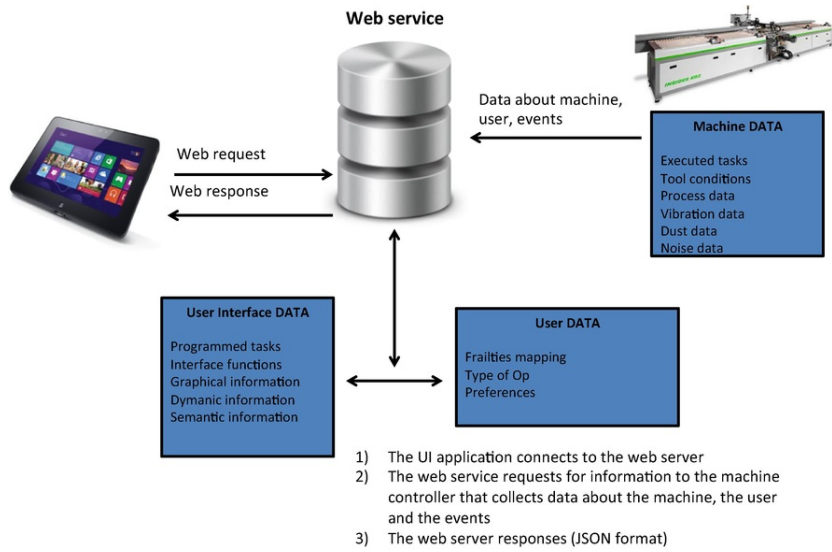
Fig. 8 The AMS prototype IT system set-up.

As a consequence, the interface could be configured according to the worker needs: for instance, if the specific operator had some vision problems, the interface graphics was configured according to him/her needs; if the operator had problems of memory or concentration, the interface displayed information in a proper manner; if the operator had limited motion abilities, the tasks were adapted according to him/her faculties, etc. The joint action of known information about the workers' workability and preference, and the effective actions allow having an efficient system adaptation. Adaptation aims at reducing both physical and cognitive workload by reducing and optimizing the manual intervention (only when necessary, and in the easier and most comfortable way).

Figs. 9 and 10 show some examples of the machine context-aware adaptation in order to simplify the human tasks and improving the worker's comfort. Fig. 10 shows the redesign of the UI: the latter is clearer, more synthetic, understandable, and friendly. The detailed list of implemented CBR algorithms and machine decisions cannot be included due to paper length limit.
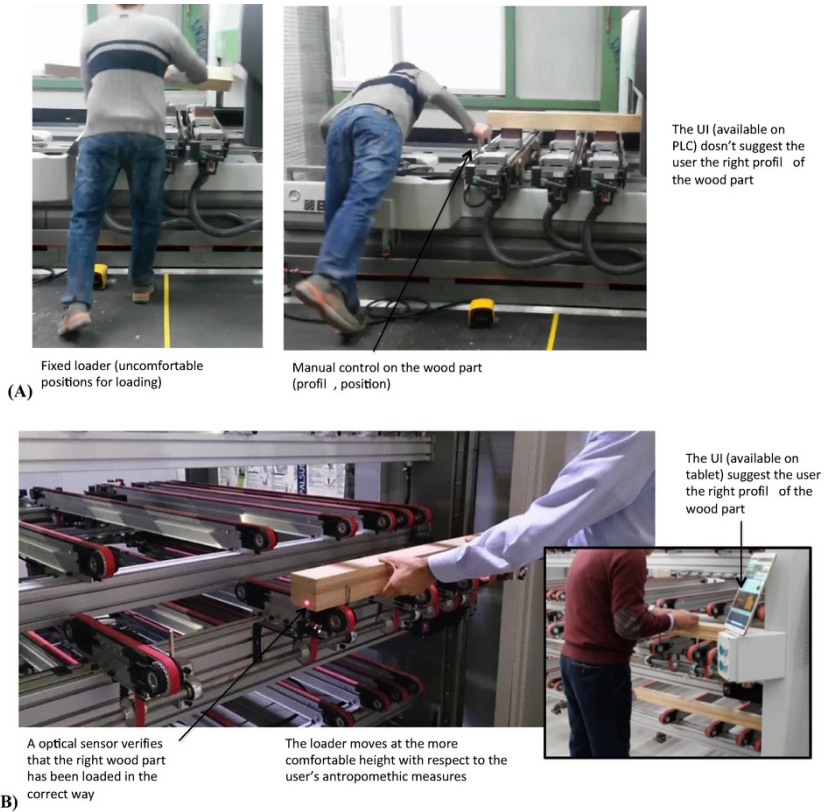
The UI (available on PLC) dosn't suggest the user the right profil of the wood part

Fixed loader (uncomfortable positions for loading)

Manual control on the wood part (profil, position)

(A)

The UI (available on tablet) suggest the user the right profil of the wood part

A optical sensor verifies that the right wood part has been loaded in the correct way

The loader moves at the more comfortable height with respect to the user's antropomethic measures

(B)

Fig. 9 Example of machine context-aware adaptation – machine loading before (A) and after (B) adaptation.

The machine automatically defins the height of the tool in order to improve the user comfort furing tooling change

The system monitors vibrationson tools and the interface makes the user aware about the tool conditions during the change
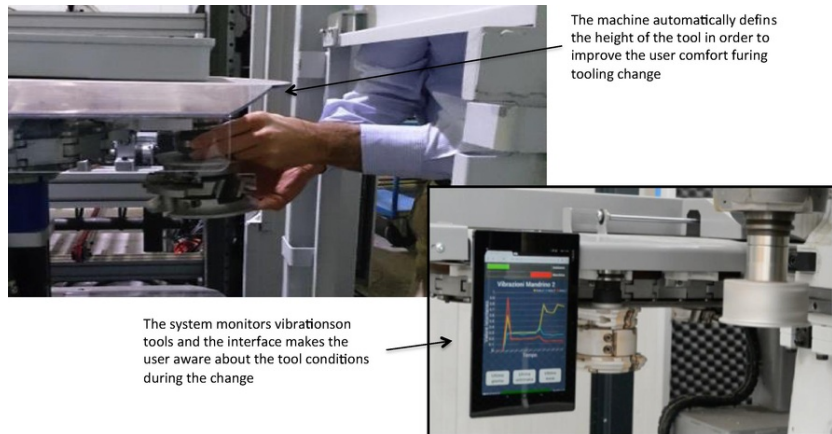
Fig. 10 Example of machine context-aware adaptation – tooling change after adaptation.

4.4 Results and discussion

In order to demonstrate the validity of the proposed approach, the new human-centred AMS was compared with the previous solution in terms of usability by tests with users on real prototypes. During the experimentation, usability has been considered as defined by ISO (International Standard Organization): "usability is intended as the ease of use and learnability of a tool, device or system, connected with the degree to which the tool can be used by specified consumers to achieve quantified objectives with effectiveness, efficiency, and satisfaction in a quantified context of use" [34]. A preliminary usability test was carried out on both the original machine tool without any adaptive behaviour, and the new AMS with human-centred adaptive behaviours. The experimental results proved an increase in both usability and acceptability thanks to the achieved human-oriented adaptation, which successfully supports the workers during task execution (according to tasks defined in Table 3).

During the tests, 10 sample users aged from 50 to 64 were involved: 70% were over-55 men and 30% were over-50 women. All users were normally employed in woodworking sector and they were affected by different "functional decreases" affecting the workability, which commonly affect middle-aged workers operating in woodworking sector, in particular:

- slight short sighting,

- minor backache that limits load lifting,

- few memory and concentration problems connected to natural aging.

It means that all users were familiar with the tasks and had some past experience on them. As a consequence, the present study did not investigate the effect of adaptation rules on non-expert users. Logically, the AMS should substantially improve the performance of non-expert users, more than of expert users. So the testing considers the situation where obtaining significant improvements is more difficult.

Experimentation focused on UI configuration and automatic system improvements (i.e., assistive loading, assistive tooling change, better labelling procedures). During experimentation, they were all considered Op1 workers. They were asked to execute a list of basic tasks as follow:

- T1. Read the status of the environment,

- T2. Read the status of the machine,

- T3. Load/unload the parts,

- T4. Read the next part label to be loaded,

- T5. Supply staples and labels,

- T6. Recognize an alert and its typology.

In order to measure the users' performance, a set of metrics was defined referring to effectiveness, efficiency and satisfaction, as reported in Table 6. Both quantitative and qualitative metrics were considered. Quantitative metrics are: execution time, number of errors or percentage, task completion. Qualitative metrics regard satisfaction in use and judges are expressed according to 1–5 scale. During task execution, metrics were measured by direct observation by experts; after tasks execution, an ad-hoc questionnaire is submitted to the users. Table 6 shows the obtained results comparing feedback on the original machine (without adaptive behaviours) and the new AMS (with human-centred adaptive behaviours designed by the proposed methodology).

Table 6 Experimental results from usability test (original system vs human-centred AMS).

Usability Dimension		Metrics	Unit of meas.	Traditional system	Human-centred AMS	%
Effectiveness		Task completion without assistance	%	70	83	+13
		Task completion with assistance	%	92	100	+8
		Average number of assistance requests	No.	5	2	−60
		Average number of errors	No.	4	1	−75
Efficiency		Average execution time	s	42	33	−21,4

	Time ratio (time/time from experts)	1/No.	0,67	0,91	+35,8
Satisfaction	Easiness of tasks (low workload)	1–5 judge	2,7	3,8	+40,7
	Simplicity in use	1–5 judge	3,3	4,2	+27,3
	Comprehensibility	1–5 judge	3,0	4,8	+60,0
	Intuitiveness	1–5 judge	2,8	3,5	+25,0
	Order perceived	1–5 judge	3,0	4,0	+33,3
	Learnability	1–5 judge	2,6	3,8	+46,1
	Familiarity	1–5 judge	3,0	4,2	+40,0

Results analysis highlighted the higher performance achieved by the new AMS in term of reduced time and errors, and the higher level of satisfaction of users achieved with human-centred adaptation. About performance, the adaptive system allows to drastically reduce the average number of errors (−75%) and execution time where the result is averaged on all the tasks considered for the test (−21%). About satisfaction, it is generally improved (+38%), with positive effects especially on comprehensibility (+60%), learnability (+46%), easiness of tasks and familiarity (both about +40%). Such positive results obtained also about system usability in terms of user satisfaction highlight how the adaptive behaviours designed effectively support the workers realizing the so-called human-centred manufacturing. Furthermore, from a design viewpoint, the VC approach was found to be useful to shorten the time needed to design and optimize the context-aware logics and the system adaptive rules thanks to the seamless interdisciplinary communication enabled by the VC environment between the cyber-ends and the physics-ends. Indeed, the virtual prototype created a clear representation of physics assets into the virtual environments and linked them to the cyber assets by advanced simulation that support designers and engineers to define the adaptive behaviours to be implemented. Finally, considering the benefits on the woodworking industrial process, the new ASM leaded to the sequent improvements:

- total reduction of the human errors (−100%);

- reduction of the manual operations (−40%;

- reduction of downtimes and stops needed to adjust the machine and to handle with problems manually (−50%);

- reduction of batch quantities (virtually until the "batch one");

- increased system production capabilities (+35%).

Despite the experimentation involved expert users, results shown good improvements. The study didn't investigate the effect of adaptation on non-expert users, on which benefits should be even bigger. Furthermore, experimentation focused on the human factors evaluation, including both physical and cognitive ergonomics, but the effect of the system automation is not evaluated, while results can be affected also by the more automated machine behaviour.

The paper focused on the definition of a design framework to define human-centred adaptive systems, and it is preliminarily tested the achieved benefits. The design of the specific AMS for the NC processing woodworking machine is considered the validation of the proposed framework. Future works will concentrate on providing a more robust framework validation of the quality and usability of the AMS created, also by inferential statistics, which falls outside the design framework validation.

5 Conclusions

The research proposed a human-centred approach to design and engineer adaptive manufacturing systems (AMS) to support aging workers in the context of Industry 4.0. Indeed, today smart factories can exploit the linkage between the cyber-ends and the physics-ends to realize an interactive environment considering the external conditions, the features of machines and interface, and the workers' capabilities. It represents a significant contribution to the design of flexible production systems, questioning about the role of human beings and focusing on how workers can improve their performance as well as the system performance. In particular, aging workers (45-64 years old) are increasingly numerous into a variety of industrial section, in Europe as well as worldwide. Understanding their needs and reduced workability due to both physical and cognitive functional decrease is fundamental to improve the design of smart manufacturing systems. Indeed, smart system can adapt their behaviours to support the workers' interaction with

machine and to improve the global system productivity. System adaptation rules can be defined taking into account not only the variability of the process parameters and the external conditions, revealed by sensors, but also the workers' functional decreases and skills. The paper describes the human-centred approach and the design methodology used to identify and develop adaptive behaviours starting from the analysis of the workers' workability. The proposed method has been implemented on an industrial case study in the woodworking machine sector, where aging workers are very common and age-related problems frequently occur. The case study described how an existing machine tool has been improved by adaptive behaviours to support aging workers thanks to CPS and proper knowledge management system architecture. Preliminary results demonstrated how the designed machine could be implemented in practice thanks to the combination of virtual commissioning and case-based reasoning algorithms. The new adaptive system was able to intelligently adapt its behaviours according to external conditions, working conditions and the specific workers' skills, tasks, and cognitive-physical abilities, thanks to a set of human-centred and context-aware configuration rules. Experimental results demonstrated how adaptation achieved positive effects on both system usability (i.e., errors reduction, comprehensibility, easy to use) and the global process performance (i.e., time reduction, downtime reduction, productivity increase). The main limitations of the proposed study are represented by the application to only one industrial case, a limited involvement of workers and machine functions, and the definition of human-centred adaptation rules, referring mainly to the system interface and those parts of the machine interested by a direct interaction with users, while a complete automatic system adaptation referring also to the process performance (e.g., higher speed, greater productivity, limitation of material wastes) is not implemented yet. For these facts, inferential statistics analysis could not be applied at this stage. Furthermore, difference between the involvement of expert and non-expert users is not considered, so that an "adaptation effect" is not distinguished.

Future works will focus on applying the proposed approach and methodology to more numerous and complex industrial cases, to involve more users in order to apply also some statistic data elaboration, to test difference between expert and non-expert users, and to detail the adaptation rules also to achieve other sustainability objectives (e.g., energy efficiency, cognitive ergonomics). Furthermore, results will be evaluated also considering the ergonomics improvements for workers.

6 Uncited references

[3,38].

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Highlights

- A methodology to design an adaptive manufacturing system (AMS) is proposed.
- The designed AMS is human-centred and considers workers' needs and working conditions.
- Knowledge-based rules and CBR algorithms allow the intelligent system adaptation.
- A virtual commissioning approach is used for simulation and features' optimization.
- An industrial case study shows an example of human-centred AMS and demonstrates the benefits.

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