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Ageing workforce management in manufacturing systems: state of the art and future research agenda

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The workforce ageing phenomenon is recently affecting most of the Organisation for Economic Co-operation and Development (OECD) member countries, due to a general ageing of their populations and a higher average retirement age of the workforce. In this paper, the topic of ageing workforce management is addressed from a production research standpoint, with the aim of understanding how older workers can be supported and involved in a manufacturing system. First, the current state of the art related to the ageing workforce in production systems is presented. This is structured according to four main topics: (1) analysis and evaluation of ageing workers' functional capacities, (2) consideration of ageing workers' capacities in industrial system modelling and management, (3) analysis and exploitation of ageing workers' expertise, (4) acknowledgement, analysis, design and integration of supporting technologies. Next, the discussion on the impact of the ageing workforce on manufacturing systems' performances leads to the comparison of some technological advances that are related to the Industry 4.0 paradigms. Finally, a future research agenda on this topic is proposed, based on the same topics classification proposed for the literature analysis. Five different research areas are derived, suggesting future directions for appropriate research concerning the employ of older workers in production environments.

Keywords: ageing workforce; human resource management; ergonomics; Industry 4.0; collaborative technologies

Introduction

The topic of ageing always attracts more interest, not only among governments, institutions and economists, but also among researchers and practitioners focused on production systems. The reason is that, together with the decrease in birth rates and the increase in people's longevity, the average retirement age in many Organisation for Economic Co-operation and Development (OECD) member countries is becoming higher. In fact, the recently published '2018 Ageing report: underlying assumptions and projection methodologies' (EC 2017) reviews the demographic developments in the EU member states and presents the long-term impact of changes in the demographic structure on the public expenditure covering pensions, healthcare and long-term care. According to this report, the European population (referring to the 28 EU member countries) is projected to grow from 507.2 million in 2013 to 522.8 million in 2060, with the percentage of seniors (65 years or older) forecasted to grow by 10%, while the working age population is expected to drop by 9.4% over the same period. A similar trend is observed in the USA, where in 2016, people over 65 years old comprised 18.6% of the adult working population (over 16 years), and this percentage is projected to grow by an average of 0.6% per year until 2026. In Japan, more than 25% of the population were aged 65 years and older in 2014, and this percentage is expected to reach 40% by 2060 (Debroux 2016; Collins and Casey 2017; The Economist 2017).

Therefore, industrial engineering and production research societies, as well as policy makers at national and business levels, have to deal with the challenge of addressing these changes in the human resource markets and, above all, with their implications for the work conditions. Tackling such issues is especially needed for workplaces where employees are required to perform manual and mental tasks, involving their physical and cognitive capacities, such as in manufacturing or assembly systems (Battini et al. 2011; Börsch-Supan and Weiss 2016; Battini et al. 2017). For example, some years ago, BMW decided to reinvent some of its assembly lines to accommodate an ageing workforce and to facilitate the performance of the most physical tasks by improving ergonomics, introducing a variable line pace and training older workers to avoid musculoskeletal disorders (De Pommereau 2012).

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To achieve such a challenging goal, it is fundamental to know the characteristics of older workers, which then allow a company to properly support and guide them in performing their tasks (Barrios and Reyes 2016; Strasser 2018). According to various research reports (Casey, Metcalf, and Lakey 1993; Walker 1997, 1999, 2002), the five main dimensions of age management in public and private organisations are: job recruitment and exit; training, development and promotion; flexible work practices; ergonomics and job design; changing attitudes towards ageing workers. In this context, industrial and production engineers should also be involved by studying and proposing analysis techniques, measures or tools for managing and involving older workers (Strasser 2018).

This paper contributes to the age management knowledge from the perspective of industrial engineering and production research. It focuses on the study of older workers in production systems where human operators' functional capacities (both physical and cognitive) are still central resources, such as in manufacturing and assembly facilities (Osaki, Wada, and Kikuchi 1980). Starting from the analysis of the current trend of workforce ageing and from a systematic literature review on this topic, a classification framework of the body of research developed so far is derived. This helps in the subsequent discussion on the open points and the topics that certainly need further investigation.

The remainder of this paper is structured as follows. In Section 2, a systematic literature review related to the study on older workers in manufacturing systems is presented, in which the selected papers are classified according to their contents and findings. In Section 3, ergonomics and the latest-generation assistive technologies for age-friendly workplaces are discussed and compared, also through the introduction of a summarising table. Finally, a framework and a research agenda for future efforts on this topic are provided, and conclusions are presented.

Literature analysis on ageing workforce

Literature search and classification of relevant papers

To understand the current state of the art about workforce ageing, a systematic literature search based on Neumann and Dul's (2010) proposed methodology has been performed. The focus is on understanding how ageing is considered and studied in production research, limiting the study to the contributions that show clear and useful applications for manufacturing systems and that possibly aim to use an engineering approach. The literature search consists of three consecutive steps: defining relevant keywords, searching the Scopus database and identifying relevant papers.

The definition of the keywords follows the scheme reported in Figure 1. The words *ageing/aging/older* or *elder* combined with *workforce/worker* have been considered; these have been further combined with *assembly/industrial/production*

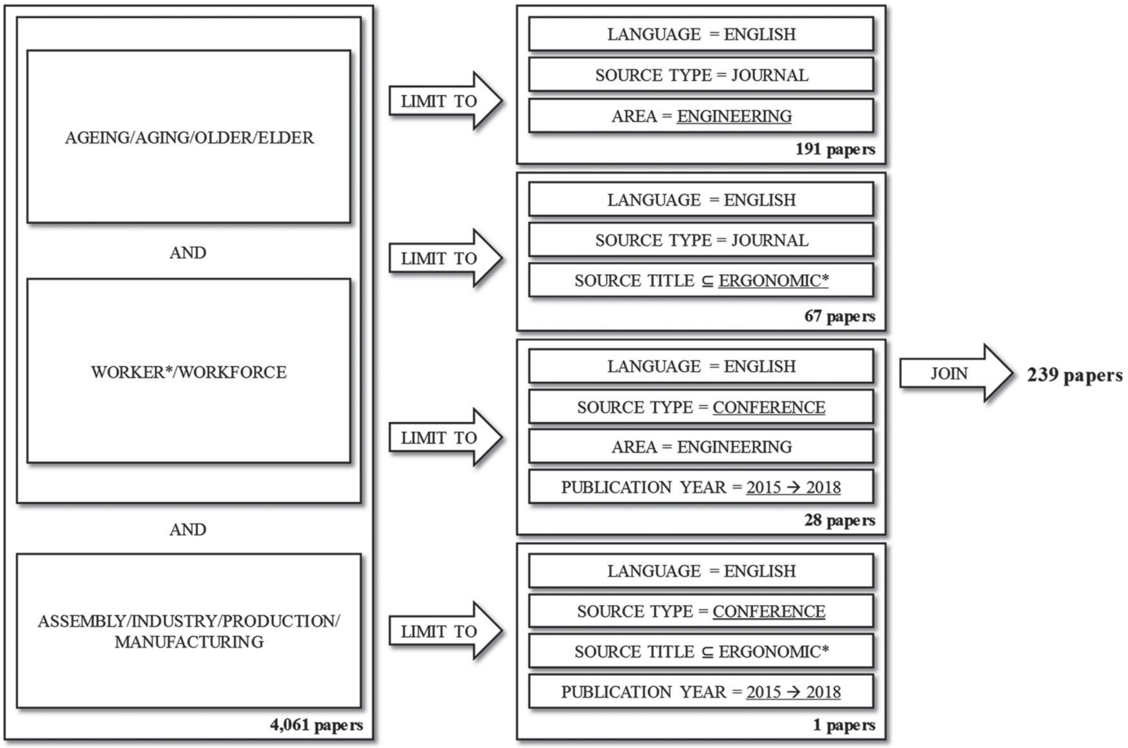

Figure 1. Keywords and approach of the literature search.

or *manufacturing*. All the possible combinations of these keywords have been searched in the Scopus database, resulting in a total of 4,061 papers. This initial search has then been refined according to four different combinations of criteria, considering English as the language, the source type (journal or conference proceedings), the subject area (engineering) or the source title (including the word *ergonomic**). For the conference proceedings, it has been decided to limit the search to the years from January 2015 to November 2018 to generate only the more recent contributions, which could differ from the journal publications since the latest conference papers have probably not yet been published in journals. The final number of papers obtained from all these searches, disregarding the duplicate entries, is 239.

This list of 239 papers has been further reduced by examining their contents, reading all the titles and the abstracts and deriving a list of 86 relevant papers (69 published in journals and 17 in conference proceedings). The two main relevance/exclusion criteria are as follows: the paper should present research related to manufacturing and production systems, and it should highlight or provide useful insights about an ageing workforce.

Based on the contents and the findings of the 86 papers selected from the literature search, the classification reported in Table 1 has been derived. It has been decided to distinguish the papers according to two main categories: those related to *human resources* and those to *supporting technologies*. In the first group, the papers have been further divided into two sub-categories: *functional capacities* and *experience*. The functional capacities topic includes 40 papers that study the performances of older workers and 12 papers that aim at modelling and/or proposing methods for managing these performances, from both physical and cognitive perspectives. The experience topic covers the papers that, through different approaches, acknowledge a potential advantage derived from the experiences of older workers (14 papers) or further show how to exploit such expertise in production (3 papers).

In the second group, the papers dealing with supporting technologies are divided into two sub-categories: six papers that point out the need for studying and developing new technologies and systems for an ageing workforce and 11 papers that specifically propose systems and devices for helping older workers.

An interesting analysis of the selected papers is related to the countries of the authors and the geographical areas where the studies have been conducted. In particular, 41 papers are from Europe (6 from Germany, 5 from France and 5 from Finland), 23 are from the USA, Canada and Mexico; 12 are from Japan; 5 are from South Korea and 5 are from other countries. If the publication year is considered, a trend showing a slight increase in the number of contributions is noticeable in recent years.

Further details about the various papers according to the proposed classification are reported in the following sub-sections.

Human resources

Analysis and evaluation of ageing workers' functional capacities

In a manufacturing environment, human operators' functional characteristics are generally related to their capabilities of performing a certain set of tasks, requiring physical and/or cognitive efforts. As demonstrated by some contributions, such capabilities can diminish with ageing (Gonzalez and Morer 2016; Strasser 2018); however, this decrease can have or not have an actual impact on the system's productivity.

The body of research related to the study of the functional characteristics of older workers started at the end of the 1970s. These studies can be classified into three types: those focused on physical performance, those concentrating on cognitive performance and those investigating both physical and cognitive performances (Table 1).

The first studies that deal with physical performance, particularly with the investigation of physical limitations of older workers, are by Aunola, Nykyri, and Rusko (1978, 1979). Here, the physical strain of employees working in machine and manufacturing industries was analysed, pointing out the relation between relative strain and the workers' age. Pennathur, Contreras, et al. (2003) measured manual dexterity, which turned out to be the worst for older workers, while Kang, Woo, and Shin (2007) observed a general lower physical capacity of older workers in the Korean metal industry. Chung and Wang (2009) highlighted how different age and gender groups tend to have different capabilities in joint mobility, with an age-induced decline, particularly in the cervical spine and the wrist joint. Qin et al. (2014) analysed the development of shoulder muscle fatigue during a repetitive manual task, as examined through Electromyography (EMG) sensors; older adults tended to develop muscle fatigue faster, with a potential higher risk of musculoskeletal symptoms in the trapezius muscle. Chen et al. (2017) studied the effects of age on psychophysical estimates of maximum acceptable lifting loads, showing that older workers selected maximum acceptable lift masses that were (on average) 24% lower than those picked by younger workers.

Linked to this group of studies, others propose insights related to musculoskeletal disorders and injuries (Neumann et al. 2018). Snook (1987) and Chung and Kee (2000) observed work-related back problems or injuries, especially among older workers. In particular, Snook (1987) recommended a proper match between the worker and the job to reduce work-related injuries and illnesses, as well as improvements in job performance and job satisfaction. Landau et al. (2008, 2011) identified long-term cumulative effects on musculoskeletal disorders; older workers suffer from lumbar spine or head–neck–shoulder

Table 1. Classification of the relevant papers.

HUMAN RESOURCES					SUPPORTING TECHNOLOGIES	
FUNCTIONAL CAPACITIES				EXPERIENCE	PHYSICAL TASKS	COGNITIVE TASKS
PHYSICAL			COGNITIVE			
Functional capacities analysis and evaluation of ageing workers				**Experience analysis and evaluation of ageing workers**	**Need for support systems acknowledgement and analysis**	
Aunola, Nykyri, and Rusko (1978) Aunola, Nykyri, and Rusko (1979) Kochhar (1985) Rowe (1985) Snook (1987) Marszalek et al. (2000) Jeong (1999) Chung and Kee (2000) Gaudart (2000) Marszałek (2000) Räsänen, Laitinen, and Rasa (2000) King (2002) Pennathur, Contreras, et al. (2003)	Pennathur, Magham, et al. (2003) Rouch et al. (2005) Kang, Woo, and Shin (2007) Landau et al. (2008) Lindroos et al. (2008) Saremi et al. (2008) Sörensen et al. (2008) Verma et al. (2008) Chung and Wang (2009) Kawakami and Yamanaka (2009) Blok and de Looze (2011) Landau et al. (2011) Carrillo-Castrillo et al. (2016)	Fritzsche et al. (2014) Neupane et al. (2014 Qin et al. (2014) Xu et al. (2014) Thetkathuek et al. (2015) Van de Ven et al. (2016) Binoosh, Mohan, and Bijulal (2017) Chen et al. (2017) Gilles et al. (2017) Hibino et al. (2017) Moraru, Cioca, and Babut (2017) Nardolillo, Baghdadi, and Cavuoto (2017)	Kochhar (1985) Gaudart (2000) Räsänen, Laitinen, and Rasa (2000) Rouch et al. (2005) Schwerha, Wiker, and Jaraiedi (2007) Sörensen et al. (2008) Wiker, Schwerha, and Jaraiedi (2009) Blok and de Looze (2011) Fritzsche et al. (2014) Neupane et al. (2014) Van de Ven et al. (2016) Gilles et al. (2017) Moraru, Cioca, and Babut (2017)	Belbin and Stammers (1972) Cooke and Blumenstock (1979) Laflamme and Menckel (1995) Laflamme (1996a) Laflamme (1996b) Anon (2000) Lombardi et al. (2009) Pueyo, Toupin, and Volkoff (2011) Arezes and Miguel (2013) Rohani et al. (2016) Volberg et al. (2017) Srilakshmi and Kulkarni (2018) Strasser (2018) Abubakar and Wang (2019)	Shephard (2000) Amasaka (2007) Thun, Größler, and Miczka (2007) Bouma (2013) Bures and Simon (2015) Barrios and Reyes (2016)	
Consideration of ageing workers' capacities in industrial system modelling and management				**Exploitation of ageing workers' experience**	**Design and integration of support systems**	
Williamson (1989) Nagata (1991) Ellis, Pines, and Allaire (1999) Kawakami et al. (2000) Kumashiro (2000) Olstein (2005) Kawakami et al. (2006) Weichel et al. (2010) Kumashiro (2014) Boenzi et al. (2015) Jeon, Jeong, and Jeong (2016) Botti, Mora, and Calzavara (2017)				Giannoglou et al. (2016) Abubakar and Wang (2018) Battini et al. (2018)	Duan et al. (2012) Del Fabbro and Santarossa (2016) Gonzalez and Morer (2016) Katayama, Miyoshi, and Terashima (2016) Ngo, Sommerich, and Luscher (2016) Noh et al. (2016) Oba and Kakinuma (2016) Saggiomo et al. (2016) Sanders (2016) Asaga, Yamato, and Kakinuma (2017) Borzelli, Pastorelli, and Gastaldi (2017)	Duan et al. (2012) Del Fabbro and Santarossa (2016) Gonzalez and Morer (2016) Ngo, Sommerich, and Luscher (2016) Saggiomo et al. (2016) Sanders (2016)

symptoms and upper limb problems despite the low demands imposed by their present jobs. However, Carrillo-Castrillo et al. (2016) pointed out that in their case, older workers are not at higher risk of musculoskeletal disorders than their younger counterparts since the first group usually performs less demanding tasks in the same occupations. The analyses by Jeong (1999), Lindroos et al. (2008) and Verma et al. (2008) focused on injuries; these all found that the frequency and the severity of injuries increase with age. Hibino et al. (2017) observed that older workers have a high probability of being affected by diseases, with the consequent need for substitute workers.

Other studies focused more on the work environment and on how this can affect older workers' physical performance. Rowe (1985) examined the lighting of industrial plants, emphasising that the right lighting should take into account the ages of the workers since older eyes need more light. Marszalek et al. (2000) and Marszałek (2000) analysed workers' reactions to heat stress conditions, reporting a potential greater risk of dehydration among older employees. King (2002) compared the relationship between age and discomfort ratings associated with standing on a hard floor and on a mat. The older subjects tended to record higher discomfort ratings on their feet and hips while standing on a wooden floor but greater leg fatigue and discomfort on their feet and low back when standing on a mat. Pennathur, Magham, et al. (2003) reviewed the available instruments and techniques to quantify older adults' physical activities and caloric intake, useful for an accurate assessment of the performed physical activities and the suitability of the industrial environment.

Saremi et al. (2008) showed the effect of noise exposure on workers' fatigue, with an interesting interaction between age and noise exposure, as well as between age and shift work. Kawakami and Yamanaka (2009) argued that the environment of today's industrial workplace is not particularly suited to middle-aged and older workers, specifically regarding temperature control. Thetkathuek et al. (2015) reported a study on cold exposure and health effects among frozen food-processing workers, showing that older workers have a higher risk of developing back pains. Nardolillo, Baghdadi, and Cavuoto (2017) observed differences between young and old workers, inferring that workplace tasks should consider age classification when designing work structures for employees.

Contrary to the findings and the arguments discussed so far, two studies concluded that the employment of older workers does not particularly affect the performance of a production system. Xu et al. (2014) demonstrated that age has no significant effect on the movement time during machine-paced assembly tasks. According to Binoosh, Mohan, and Bijulal (2017), although older and more experienced groups of workers showed significantly increased fatigue, this appears not to affect their performance more than that of younger workers.

Only two studies exclusively deal with cognitive performance of old workers. Both Schwerha, Wiker, and Jaraiedi (2007) and Wiker, Schwerha, and Jaraiedi (2009) investigated the impacts of age and years of formal education on learning a manual assembly task in the presence of visual and auditory distractors among 18–65 years old workers. It has been found that the oldest group of workers required significantly more trials to learn the task than the youngest one.

On the other hand, some research tackles both physical and cognitive performances. Among others, several studies demonstrated how older workers have lower performances in not only body movements but also decision processes (Kochhar 1985; Fritzsche et al. 2014; Gilles et al. 2017).

Rouch et al. (2005) focused on shift work and the possible difficulties of older workers in doing it. These authors noted no clear interaction between age and shift work. A similar finding is derived in Blok and de Looze's (2011) literature review; although some differences between older and younger workers are reported, it is concluded that there is no evidence of more shift work problems among older workers. In contrast, Van de Ven et al. (2016) found that older shift workers report shorter sleep duration, more disturbed sleep and more complaints on waking up.

Some of the authors are more concerned about the impact of the work conditions on ageing workers' wellbeing. Gaudart (2000) proposed a case study for a better understanding of why some older workers were excluded from certain workstations and, thus, why job rotation decreases with age. Sörensen et al. (2008) examined the relationship between perceived work ability and health-related quality of life, as well as their associations with middle-aged men's physical activity and cardiorespiratory fitness. Räsänen, Laitinen, and Rasa (2000) and Neupane et al. (2014) investigated the eventual relationship between age and general job satisfaction, also considering job characteristics, the work environment and psychosocial variables.

Finally, according to a more recent work by Moraru, Cioca, and Babut (2017), the decrease in physical and cognitive abilities related to ageing does not necessarily affect performance and productivity. This study reported that there is no need to treat older workers differently from younger workers, as long as employers are aware that with age, physical and mental capabilities are slightly reduced.

Consideration of ageing workers' capacities in industrial system modelling and management

Once physical and cognitive performances are studied, it would be worthwhile to develop useful models and techniques to describe such behaviours, properly take them into account and then manage and support older people in their work environment. Börsch-Supan, Härtl, and Ludwig (2014) and Börsch-Supan and Weiss (2016) have conducted recent studies precisely in this direction.

Nagata (1991) started from the analysis of fatal falls during occupational tasks, deriving a logarithmic linear relationship between age and falls and proposing exponential equations to predict fatality rates. Moreover, Ellis, Pines, and Allaire (1999) and Kawakami et al. (2000) focused on the development of manufacturing systems that are easily usable by all ages to allow older workers to maintain their independence and productivity. Ellis, Pines, and Allaire (1999) proposed a method to estimate human reliability in a work environment, also considering the differences among workers in terms of age. Kawakami et al. (2000) defined an evaluation index by measuring the time of motion elements, the cycle time per product and the motion velocity waves, compared with the motion characteristics of young workers.

Recently, Weichel et al. (2010), Boenzi et al. (2015), Jeon, Jeong, and Jeong (2016) and Botti, Mora, and Calzavara (2017) have proposed alternative job rotation schedules by taking into account workers' age-related differences, especially for workplaces characterised by low load manual tasks with a high frequency of repetition (e.g. assembly lines). The purpose is to balance tasks and workloads to enhance workers' productivity and reduce musculoskeletal disorders and absenteeism.

Other studies preferred a higher level of analysis, suggesting management or strategic techniques for an ageing workforce, also taking into account retirement policies and the employment of support systems and new technologies (Williamson 1989; Olstein 2005). Kumashiro (2000) and Kawakami et al. (2006) suggested considering methods of determining job capacity and enabling the effective use of the labour of ageing workers, through job enlargement and automation as well.

Finally, Kumashiro (2014) also pointed out the need for a long-term perspective and an integration of ergonomic considerations in systems design.

Analysis and exploitation of ageing workers' expertise

Although older workers could present an eventual physical and cognitive decline, they could constitute a useful and important resource due to their experience. This fact was earlier acknowledged by Belbin and Stammers (1972) and further confirmed by Anon (2000) and Srilakshmi and Kulkarni (2018); according to their studies, older workers would be able to compensate for their lack of energy during manual tasks with higher skills and knowledge in performing their jobs or even in new occupations. This is demonstrated also by the study of Abubakar and Wang (2019), which showed that experience is the most significant human factor that affects individual human performance, compared to age and general cognitive abilities in human-centred assembly.

Another effect related to experience is the possible decrease in certain work injuries (Volberg et al. 2017). For example, the reason could be older workers' better knowledge of the work environment and how to correctly perform a certain task (Cooke and Blumenstock 1979; Laflamme and Menckel 1995; Rohani et al. 2016). In some cases, a lower injury rate could also be because older workers are less exposed to injuries compared with younger workers since the first ones have been moved to less dangerous and less demanding tasks (Laflamme 1996a, 1996b).

Linked to the decrease in injuries, older workers also practise more conscious usage of individual protection systems, for example, for the eyes and the ears (Lombardi et al. 2009; Arezes and Miguel 2013). Another cause could be a more cautious approach in performing a certain set of tasks (Pueyo, Toupin, and Volkoff 2011; Strasser 2018), where older workers demonstrate a greater inclination to plan their work ahead and identify critical situations to avoid or limit them and exercise a higher level of autonomy.

As far as the exploitation of ageing workers' experience is concerned, Giannoglou et al. (2016) reported the basic idea of the 'Elders-Up!' project, which aims to bring and to transmit senior adults' valuable experience to start-ups and small companies through the development of an integrated online platform. More recently, Abubakar and Wang (2018) proposed a Discrete Event Simulation model incorporating experience and ageing attributes of workers, which has been used for modelling a linear human centred assembly line operated by workers of different ages. Finally, Battini et al. (2018) suggested to include older workers' experience in one of the possible uses of the presented VR- Ergo Log motion capture system. Indeed, it is proposed to use the VR-Ergo Log system to perform virtual training of younger and less expert workers by involving ageing and expert ones, in order to avoid wrong and non-ergonomic movements and procedures.

Supporting technologies

As stated, ageing workers are subject to progressive physical and cognitive decline, together with knowledge and experience acquisition. To face this trend and to properly support older workers, some authors suggest considering the use of support systems.

Shephard (2000) and Bures and Simon (2015) pointed out the need for redesigning workplaces (possibly by making them adaptable to the employees' ages and characteristics) or for developing adequate collateral initiatives to upgrade older workers' productivity, such as retraining, wellbeing improvement and human resource involvement. In a similar direction, Thun, Größler, and Miczka (2007) and Barrios and Reyes (2016) stated that a possible solution for the employ of older workers could be the automation of workstations by taking advantage of new technologies as well. Bouma (2013) preferred to focus on solutions considering ergonomics and human factors associated with older workers, such as increased light during the performance of certain tasks, wearing of proper glasses and varied work postures. A different strategy is the one of Amasaka (2007), who concentrated more on organisational and managerial aspects. The study reported about Toyota's automotive assembly lines with a new just-in-time approach and on the changes that can be introduced to make them more suitable for ageing workers through an increase in worker motivation, workload reduction and work environment improvement.

Regarding the support and the integration of systems design, the literature search highlights that the existing contributions are quite recent and mostly from conference proceedings, indicating that this represents an ongoing topic that has attracted interest in the ergonomics and engineering literature in recent years.

For example, some researchers propose tools and devices for aiding workers' physical capacities. This is the case of Katayama, Miyoshi, and Terashima's (2016) study, dealing with a power-assisted system to help older workers in handling overhead cranes. Noh et al. (2016) and Borzelli, Pastorelli, and Gastaldi (2017) recommended wearable exoskeletons, for the back and for the arms, respectively, that are able to amplify the worker's input force or torque. Oba and Kakinuma (2016) and Asaga, Yamato, and Kakinuma (2017) studied manual tasks in automotive manufacturing (i.e. repair polishing and buffing processes) and suggested developing a skill-independent automation technology that is able to support and, in some cases, replace the worker.

Different approaches can be proposed in the case of support systems for both physical and cognitive capacities. Duan et al. (2012) described an assembly system that combines both the dexterities of human operators and the advantages of automated machinery through collaboration between the operator and twin manipulators, assembly information guidance and a safe design for collaboration. Similarly, Saggiomo et al. (2016) explained an augmented reality-based assistance system in connection with up-to-date textile machinery.

Del Fabbro and Santarossa (2016) and Ngo, Sommerich, and Luscher (2016) investigated new tools and software models for simulating the manufacturing process and obtaining a precise ergonomic analysis before building (at the manufacturers' disposal) any physical prototype to perform the assessment, also taking into account a worker population that is diverse in stature, weight and age.

Both Sanders (2016) and Gonzalez and Morer (2016) presented recommendations for the design of support systems. The first one is based on the body of evidence obtained from a multiple case study. The second one derives a theoretical framework from contributions of the literature and of practitioners, useful for the development of a design guidance tool for an inclusive workstation design.

Ergonomics and latest-generation equipment for age-friendly workplaces

As discussed in the previous sections, there is a strong need to change work processes due to imminent demographic changes. Several ways to approach the demographic changes, with a shrinking workforce and an increment in older workers, are to integrate workers' knowledge faster, support (older) workers in their tasks and enable longer employment of workers so that they can further contribute to their country's economy. To meet these challenges and permit an ageing workforce to work productively and comfortably in the manufacturing systems of the future, one of the major problems is the integration among ergonomics (Battini et al. 2011), neuro-ergonomics (Parasuraman 2003) and the human factor design principles (Proctor and Vu 2010) in order to define age-friendly workplaces and processes (Sun et al. 2018). In the past, ergonomics had always aimed at designing tools and work environments that were comfortable and suitable for human use (Zennaro et al. 2019). Currently, the objectives of ergonomics can be identified as the usability and the safety of systems where the operator is considered a unique user and an integral part of each system. This means that each worker is different from the others, and physical and cognitive diversity should be taken into account. Both external factors (e.g. the industrial environment, the number of ageing workers involved, the work hours etc.) and internal factors (e.g. personality, demographic background, work background, skills, special needs of older workers etc.) influence the ergonomic design of the workplace. This workplace should also respond to specific workers' needs in order to increase their motivation, job satisfaction, creativity and work performance quantity and quality (Sun et al. 2018).

The final aim is to provide ageing workers with the best age-friendly workplace, where their extensive work experience and high-level skills can be empowered and driven in the best way, first of all, in knowledge-intensive settings. In this context, technological advances provide valuable assistance. According to the well-known paradigm of Industry 4.0, digitalisation and information technologies are the instruments that help manufacturing systems respond to future challenges. In particular, smart manufacturing is the major area of current investment in Industry 4.0 in Europe (EC 2015a).

The new digital industrial revolution holds the promise of increased age-friendly work environments since the smart manufacturing initiatives are the most financed at present. Inside a smart manufacturing environment, a set of connected devices and intelligent systems collaborate with humans, without replacing them but enlarging their capabilities and empowering their capacities. In this case, an older worker actually becomes a 'technology augmented master crafts man' (Kusiak 2018; Bogataj et al. 2019).

Collaborative robots, together with the latest-generation lifting and handling devices, allow companies to automate highly complex and low ergo-quality tasks by assisting humans in their manual tasks. Operators can also receive more support by wearing exoskeletons (Noh et al. 2016; Borzelli, Pastorelli, and Gastaldi 2017). For example, upper body exoskeletons elevate and support a worker's arms during overhead tasks and provide adjustable lift assistance of 5–15 lb per arm. Exoskeletons can be unpowered (merely cancelling the effects of gravity) or powered with batteries to boost lifting performances of human operators. Intelligent smart tooling and augmented reality devices can support older workers in remembering information, procedures and correct tool setting during production, thus improving productivity and minimising idle times (Yuan, Ong, and Nee 2008; Ong, Yuan, and Nee 2008; Gonzalez and Morer 2016; Takahashi, Kudo, and Ishiyama 2016).

For a particular task, an older employee can be quickly directed to the right tool that automatically 'knows' the next step and sets the correct calibration for the specific part that the employee wants to tighten. The so-called smart tools can also record the operation to ensure quality control and eliminate manual logging (Gorecky et al. 2014; Takahashi, Kudo, and Ishiyama 2016). Another example is a pair of data glasses, which delivers visual instructions to humans in order to provide assistance in machine repair, product assembly, product quality control and so on. Moreover, augmented reality-based exoskeletons can also be applied for virtual object assembly training (Hoedt et al. 2017).

Table 2 compares the main ergonomics and work-assistance equipment solutions for improving the ergonomic level and the productivity of assembly and production processes according to the Industry 4.0 paradigms (Liao et al. 2017; Xu, Xu, and Li 2018). This table briefly describes each system, its benefits and limits, as well as presents a qualitative evaluation of the necessary investment in order to compare them from an economic perspective, by considering both purchase and installation costs. The benefits discussed in the table are related to the advantages gained by using each device and the impacts on the overall system. On the other hand, the limits explain the disadvantages for human operators and their possible impacts on manual work.

However, at this stage, to capture the benefits of technology in solving the ageing workforce problems, enterprises will need to invest a large amount of money in new ergonomic equipment that is older worker oriented and ad hoc designed to meet personal needs. These investments can be particularly daunting for small- and medium-sized enterprises (SMEs), which often cannot assess how such devices and technologies may affect their value chains. Moreover, some systems are too expensive, unreliable and oversized, and in some cases, there is also the risk for a SME to be driven largely by equipment producers rather than customer demand (Davies 2015).

Future research agenda

In the light of the discussed considerations, the authors have attempted to determine which directions might be fruitful for future research on the ageing workforce in industrial systems in order to address the manufacturing systems' current problems that have not yet been assessed by the mainstream traditional literature. The research agenda described in this section is based on and directly derived from the analysis of the literature provided in Section 2 and from the literature classification proposed in Table 1.

The authors have identified five main research areas for further development in the future to respond to the main industrial system needs; these are reported in Figure 2. The first research area pays attention only to human resources, while the second focuses the analysis on new support systems' design and development for the industrial systems of the future. The subsequent three research areas integrate the aspects linked with human resources (functional capacities and experience) into the technological aspects that should be considered when humans and active power-supporting devices cooperate in the same industrial environment and workspace.

Detailed descriptions of each research area is reported in the following.

Research area 1: real data collection, field studies and case studies to provide new data sets for age-related measurements

The literature analysis provided in Section 2 indicates a low amount of recent real data set collection and analysis research especially related to ageing workers. This research area would help in the study of how ageing workers perceive and work

Table 2. Technology solutions to improve the ergo-level of manual activities (benefits, limits and investment levels).

System	Description	Benefits (impacts on work)	Limits for operator	Investment	References
Lifting and material handling device	Equipment that assists or helps the operator in moving and picking objects and parts and/or during the assembly tasks (i.e. lift, articulated arm manipulator, vacuum tube lifting device, sub-assembled moving device, smart AGV/LGV, etc.)	• Increased efficiency and time savings for handling activities • Improvement and facilitation of assembly and picking activities (easier access, right mounting direction display) • Avoidance of musculoskeletal disorders and back pain	• Potential restriction of possible material movements and placements in a certain area • System availability (failures could compromise worker operation) • Operators are more stationary	Low	Karande and Chakraborty (2013) Rossi et al. (2013) Grosse et al. (2015) Kousi et al. (2018)
Exoskeleton	Technical device worn by the operator, which allows a direct exchange of mechanical power and information signals. It can be active (actuated) or passive (non-actuated).	• Ergonomic assistance for assembly, warehousing and handling activities (particularly for heavy lifting and overhead work) • Physical effort reduction, with the potential limitation of work-related injuries • Longer and safer productivity of operators (short and medium term) because they get tired less quickly • Longer and safer productivity of operators (long term), referring to the employment of an ageing workforce	• System weight and discomfort could reduce the operator's acceptability • Potential limitation during some body movements • Safety issues (for active ones) • System availability (failures could compromise worker operation, for active ones)	Low (passive) Medium-high (active)	De Looze et al. (2016) Spada et al. (2017) Theurel et al. (2018)
Intelligent/smart tool	Advanced active tool that is able to communicate and adapt itself to the environment of use, the operator and the product, with the possibility of also communicating and interacting with other tools	• Easier tool setting: the tool automatically knows the next activity and sets the correct calibration • Quality control: record of the operations and elimination of manual logging • Enhanced productivity: less waste of time in tedious activities (e.g. logging, calibration, etc.), fewer errors, availability of the right information when needed • Possibility of real-time monitoring and data collection	• System availability (failures could compromise worker operation) • Job impoverishment	Low-medium	Takahashi, Kudo, and Ishiyama (2016)

(*Continued*).

Table 2. Continued.

System	Description	Benefits (impacts on work)	Limits for operator	Investment	References
Augmented reality	Use of technologies and devices to create, in real time, an enhanced current perception of the reality (through graphics, videos, sounds or smart glasses, data glasses, etc.)	• Improved quality: proactive signalling and avoidance of errors • Increased productivity: faster search and processing of needed information • Reduced training effort for new operators since they will be assisted during the job by the augmented reality environment	• Potential sight fatigue when changing from near vision to long vision • System weight and discomfort • Job impoverishment • Pressure/stress due to fast information arriving at the same time • System availability (failures could compromise worker operation)	Medium-high	Ong, Yuan, and Nee (2008) Ong and Nee (2013) Paelke (2014)
Collaborative robot	Robot that can physically interact with operators during assembly and manufacturing activities (i.e. handling and positioning of components), sharing the workspace	• Simplification of operators' tasks • Cobots can substitute humans only in the most not-ergonomic tasks • Improved quality due to joint human–robot monitoring of the work output • Space and cost savings due to sharing of the workspace • Increased worker responsibility in terms of workplace safety	• System availability (failures could compromise worker operation) • Safety issues • Ergonomics issues during the direct collaboration human-cobots	High	Krüger, Lien, and Verl (2009) Tan et al. (2009) Michalos et al. (2015) Liu et al. (2019)
Smart workstation	Workstation with adjustable devices and systems, able to adapt itself to the operator's characteristics and needs. Usually equipped with an active recognition system that captures and obtains the anthropometry of the worker, it can also include lifting and material handling smart systems, AR technology and smart tools.	• Improved workplace wellbeing due to a personalised workspace • Greater system flexibility: different operators can use different workstations • Active assistance and feedback to operators during assembly processes (e.g. digital guidance, poka-yoke solutions etc.) • Faster and more intuitive operator training and employment in different production environments • Improved quality: proactive signalling and avoidance of errors • Increased productivity: faster search and processing of needed information	• System availability (failures could compromise worker operation) • Job impoverishment	High	Shikdar and Al-Hadhrami (2007) Shikdar, Garbie, and Khadem (2011) Garbie (2014) Gorecky et al. (2014) Kusiak (2018)

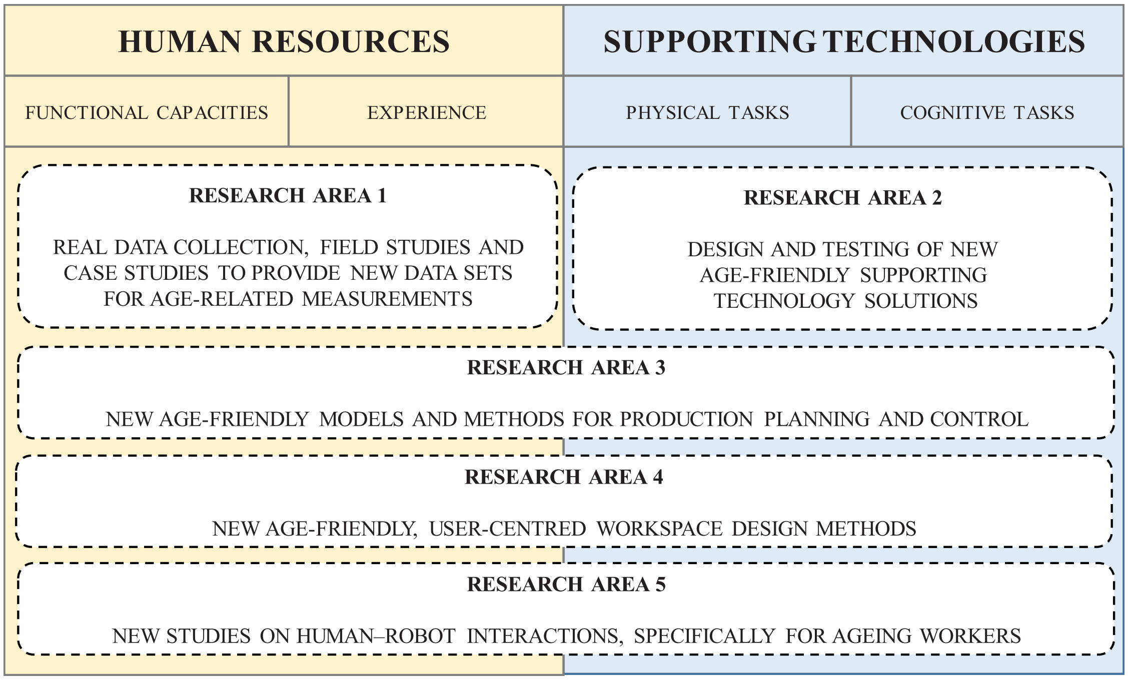

Figure 2. Five future research areas in industrial engineering for designing future age-friendly industrial systems.

in manufacturing systems, how their age affects their performances (productivity and quality of their work) and how the adoption of assistive technologies influences their productivity and motivation levels in different industrial sectors.

In this research area, two main topics are proposed:

Proposition 1.1. Age-related data on production systems should be collected and analysed.

Case studies and industrial data collections are urgently needed to provide operation managers with innovative and adequate business models and business strategies dedicated to older worker management in manufacturing environments. These data are also necessary to validate future age-oriented models and methods. To achieve these results, future research efforts should be directed towards case studies, field studies and statistical analyses based on real and reliable data sets from industries. Of course, the industrial data sets should be properly analysed, in order to warrant the extraction of correct features and, then, the possibility of a right data reuse.

Among a few other researchers, Neupane et al. (2014) and Gilles et al. (2017) provide an extensive collection of real data and a detailed analysis of age-related performance measures; however, for some estimations, these studies rely only on self-assessment techniques.

Proposition 1.2. New measurements should be executed in production systems to evaluate how workers' experience and functional capacities change with age.

Industrial engineers and economists could jointly contribute with their knowledge to the development of these kinds of studies that should analyse workers' experience and functional capacities. As recently emphasised by Börsch-Supan and Weiss (2016), it is important to encourage researchers to replicate data collection and measurement in order to gain a better understanding of the age-productivity profile according to different jobs and industrial sectors. The studies of Abubakar and Wang (2018; 2019) already suggest interesting insights related to ageing workers' experience and performance, pointing out the need of continuing in this direction with further researches. This turns out to be particularly relevant if the possible inverse influence that experience and physical decline can have on operators' performance is considered (Brooke 2003).

Research area 2: design and testing of new age-friendly supporting technology solutions

The utilisation of advanced supporting technologies not only provides improved work conditions but also offers workers the opportunity to prolong their careers, as pointed out in Section 2 (Gonzalez and Morer 2016; Borzelli, Pastorelli, and Gastaldi 2017).

The workspace of the future will facilitate the use of a combination of exoskeletons, collaborative robots (cobots), intelligent tools and mixed reality (MR) and virtual reality (VR) solutions to support and help humans without replacing them (Liu et al. 2019). Section 3 has presented an analysis of the current role and key limitations of existing assistive technologies.

In particular, in this research area:

Proposition 2.1. New age-friendly design principles should be elaborated for creating efficient human-assisted work stations and supporting solutions.

It is urgently needed the investigation of key design principles and use case goals for new age-friendly assistive and collaborative technology solutions (summarised in Table 2). Future efforts need to address the design and the development of new instrumental prototypes of active-power assistive equipment, especially designed for ageing workers, by escaping the creation of too expensive, unreliable and oversized equipment (Davies 2015). Here, the development and implementation of a new generation of comfortable and wearable exoskeletons to assist operators during manual handling tasks and awkward positions will play the major role (Spada et al. 2017; Theurel et al. 2018). One of the major challenging tasks will be to keep the exoskeleton weight and power consumption to a minimum, overcoming the traditional rigid structure, while promoting comfort and a soft-use of the system, especially for elderly workers.

Research area 3: new age-friendly models and methods for production planning and control

Future research must consider the presence of older workers in production and assembly system design procedures by developing new quantitative models that are able to include age-related aspects from the beginning of the analysis. The new approaches will need to integrate organisational, cognitive and physical load constraints and parameters in order to solve issues, such as assembly system balancing (the so-called ALBPs, Assembly Line Balancing Problems), Job Scheduling, Job Rotation, Resource Assignment Problems in manufacturing environments with the presence of an ageing workforce (Karwowski 2012).

In this research area, three main streams are proposed:

Proposition 3.1. New age-friendly balancing and scheduling models should be provided and validated.

The final goal is to totally rethink about the current literature by developing and validating new age-friendly analytical models (optimal, heuristics, meta-heuristics). As discussed in Section 2, the current literature shows that ergonomic parameters are traditionally applied in production and assembly system modelling by industrial engineers (Boenzi et al. 2015; Botti, Mora, and Calzavara 2017); however, the age profile of the workforce and age-related characteristics are not sufficiently emphasised (De Looze et al. 2016; Calzavara et al. 2019). Future models must reflect the needs of older workers and the differences among them (e.g. skills, functional capacities, experience levels, cognitive workload constraints, ergonomic workload constraints etc.), as well as differentiate among assembly and production tasks and human workloads according to the resources that will execute them (Abubakar and Wang 2019).

Proposition 3.2. Learning and forgetting models and applications should concentrate the attention on human diversity and in particular on age.

Differently to what has been done so far, future studies could make a big step forward by studying the characteristics of an ageing workforce into the learning curve to understand the impacts on the learning and forgetting rate (Glock et al. 2018; Bogataj et al. 2019). This could be done by considering both the decrease of cognitive and physical abilities of aged workers, as well as the need of longer rest breaks to recover during their job compared to younger workers. As a consequence, this would impact on the work assignment and on the work scheduling, but it can also help to understand when an older worker can still be considered preferable to a younger one in terms of the trade-off between physical performance and cognitive knowledge (Brooke 2003). Promising findings in this field, which need to be further validated, have already been pointed out by Shafer, Nembhard, and Uzumeri (2001).

Moreover, these models and methods should also consider the presence of supporting technologies and equipment that cooperate with humans during the work (Amasaka 2007).

Proposition 3.3. Management and organisational tools should include ageing workers' characteristics.

Besides what is reported in Propositions 3.1 and 3.2, the impact of the employ of older workers should be considered also in management and organisational frameworks. This would allow to properly involve aged workers into the strategies of a company, and to develop managerial tools able to take into account the differences among workers, also from an age perspective (Kumashiro 2000; Abubakar and Wang 2018). As already stated by Olstein (2005), for example, management and organisational frameworks should focus also on preventing the negative effects of senior employees' retirement, in terms of brain drain and loss of institutional knowledge.

Research area 4: new age-friendly, user-centred workspace design methods

The design of new age-friendly workspaces capable to meet the needs of all the people using them by efficiently integrating Industry 4.0 smart solutions and collaborative equipment, as discussed in Section 3, is urgently needed.

In particular:

> Proposition 4.1. New design guidelines and technical frameworks should be developed to support the creation of user-centred workspaces.

The integration of IT and collaborative technologies and their level of complexity need further investigation to create smart, user-centred design solutions that are simple enough to build senior-enabled workplaces at affordable investment costs (EC 2015a; Battaïa et al. 2018). In particular, the promising application of Internet of Things paradigms to industry can be useful in this sense (Atzori, Iera, and Morabito 2010; Bi, Da Xu, and Wang 2014; Ardanza et al. 2019). Such workplaces should make greater use of augmented reality and VR, coupled with ergonomic simulation (as emphasised in Section 3) and supported by new age-oriented ergonomics assessment methods (Garbie 2014; Kong 2018; Yin, Stecke, and Li 2018). In this future industrial setting, the digitalisation of work environments will revolutionise the innovation of manufacturing and assembly work cells and the development and integration of all the equipment inside the workspace (EC 2015a). The design of an innovative, age-friendly and ergonomic workspace by applying Industry 4.0 paradigms and tools will become increasingly strategic for manufacturing companies and will need specific tools, guidelines and design standards. The crossroads of ergonomics, workspace design and human-assistance technology implementation (i.e. collaborative robots, lifting devices and exoskeletons) are in direct need of new systems-oriented research that will lead to clear and actionable design guidelines, especially developed for large and heavy product manufacturing systems. From this perspective, the human element and experience become crucial and irreplaceable, and the collaborative robots/equipment of the future need to learn assembly operations from humans in order to provide greater support to workers, thus improving their efficiency in physical and cognitive workloads.

> Proposition 4.2. Virtual-based design methods and technologies should be further improved and tested in real settings.

Thanks to the recent technological development, it would be possible to use VR and Immersive Reality to create a computer-generated design environment for an advanced concurrent engineering of a workplace. The virtual environment can represent one or even more possible configurations of the industrial system under study. The operator can be immersed in each one of these configurations, virtually performing all the activities that he/she normally would do during his/her job, but without needing a physical prototype of the workstation (Battini et al. 2018). The applicability of such systems needs further development, investigation and testing, in order also to better highlight their strengths and weaknesses and the potential advantages that they could bring to the design of age-friendly workstations. For example, in such a virtual environment the experience of elderly workers can be effectively used to train the younger and less expert ones.

Research area 5: new studies on human–robot interactions, specifically for ageing workers

This research area investigates the case where collaborative robotics is applied, not to replace expert older workers but to support them by providing collaborative robots that can perform the workers' non-ergonomic tasks (as discussed in Section 3).

In this research area, two possible study directions are proposed:

> Proposition 5.1. New training methods should be investigated to correctly train robots starting from workers' experience in order to guarantee ergonomics movements.

One of the aspects related to cobots that has been, for now, neglected, is related to the need of giving to the robot proper instructions to avoid wrong postures or movements of the operators. It could happen that the cobot forces the operator to take awkward positions, which could even be impossible for an old worker. Therefore, it would be useful to employ real-time motion capture systems during the training of the cobot, to track the work of the operator and to highlight possible ergonomic problems (Battini, Persona, and Sgarbossa 2014).

Moreover, in this context, the worker's expertise, acquired over years of experience and during the trial-and-error process, is deeply embedded, and this knowledge is difficult to extract, model and recode for a robot. Therefore, the co-bot would initially need to be tutored or guided by the expert worker and learn parts of the processes and process tuning to be able to subsequently help the ageing worker. In the beginning, the cobot would be just a simple assistive device to compensate for some of the physical limitations of the ageing worker. However, after some time, the cobot will be able to learn and acquire more capabilities so that the ageing worker can delegate some tasks to the cobot while focusing on the more specific or critical ones, taking advantage of the full benefits of human expertise and experience (Michalos et al. 2015).

Proposition 5.2. Human-robot interactions should be studied considering also the employ of an ageing workforce.

Recent technological progress permits robots and humans to safely share a common workspace (Table 2). Thus, new criteria, models and methods are needed in the near future to analyse human–robot interactions and behaviours in a common workspace, with particular attention to ageing workers. These should consider the positive potential of the employ of cobots and how these can help and support aged workers, as well as the limits of older operators with respect to the younger ones. Of course, this research area should continuously consider also the technological progresses related to cobots, which are always smarter and able to react to the actions occurring in the environment they work in (Ivaldi et al. 2017). One of the major challenges in this area will be to combine the possibility to provide a real time ergonomic assessment of the human body movements (as discussed in proposition 5.1) with the ability of the robot to react to unintentional contacts or wrong human movements. Some attempts are already presented in the literature; for example, Krüger, Lien, and Verl (2009) and Cherubini et al. (2016) study human–robot interactions in collaborative assembly systems and Michalos et al. (2015) discuss new design considerations for safe human-robot collaborative interactions.

Conclusion

The present survey and analysis find strong evidence that the ageing workforce issue is increasingly more relevant and discussed in the literature, reflecting the changes in manufacturing systems and the population of some countries in the latter half of the past century. In recent years, engineers, operation managers and ergonomists have taken incremental steps to incorporate ageing factors in the design of workplaces and production processes. However, this literature review clearly shows a low number of works related to this topic that have been published in engineering and technical journals. For this reason, important new challenges are expected in the near future in order to face the ageing problem from an engineering and operational perspective. In particular, the proposed research agenda suggests investigating five main aspects in the near future: collection and analysis of new real data concerning the effects of ageing on manufacturing systems, design of new assistive technology solutions for ageing workers, provision of new age-oriented quantitative models for production management and control, development of new age-friendly workspaces by efficiently integrating Industry 4.0 smart solutions at an affordable investment cost and finally, provision of new criteria and models to study human–robot interactions. These proposed study streams will help to cover the highlighted research gap, as well as to provide useful practical tools for academics and practitioners who are (or will be) facing the always greater workforce ageing challenge.

Disclosure statement

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