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A decision support system for designing win–win interventions impacting occupational safety and operational performance in ageing workforce contexts

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ABSTRACT

Many companies are facing issues related to the increasing average age of their workforce, which impacts both operational and occupational safety and health (OSH) performance. In recent years, the ageing workforce (AW) has been investigated from various perspectives by researchers, showing how companies can use different approaches to address this phenomenon, either in their OSH interventions or operational strategies. However, no studies have investigated the interrelations between these approaches. In this study, we first conducted an extensive literature review that enabled the identification of (i) the aspects of operational and OSH performance affected by the AW, (ii) the suitable types of interventions in an AW context, and (iii) the interrelations between the three. Based on this, we then present a conceptual decision support system (DSS) to assist decision makers in analysing operational and OSH performance at their workplace and defining the proper interventions for an AW context. Specifically, by considering the interrelations between the interventions and both operational and OSH performance, the conceptual DSS facilitates a win–win approach, where both operational and OSH performances are improved simultaneously by choosing the proper intervention(s). An illustrative application case is then developed to show the application of the DSS before drawing conclusions about its major strengths and limitations, and further research avenues.

1. Introduction

Due to the increasingly low birth rate and increased life expectancy, the average age of the global population is constantly increasing. According to the United Nations (2018), by the year 2050, the population aged >60 years will reach 2.1 billion, affecting both developed and developing countries.

Hence, population ageing is a current issue worldwide, and has great repercussions on the labour market. To avoid the collapse of the pension system, governments are increasing the retirement age to ensure that workers continue working for longer (Hanson and Lindgren, 2020). Thun et al. (2007) showed that by 2050 in the European Union (EU) every third worker will be aged above 50 years. In such a situation, the former weak eligibility requirements for receiving early retirement benefits will make pension systems unsustainable (Palmer, 2002). Therefore, most countries in the EU are increasing the official retirement age to more than 65 for both men and women; many member states are planning to increase the retirement age even further, leading to a further ageing of the workforce.

In some sectors, the ageing workforce (AW) does not have any particular adverse impact and can even have a positive impact due to increased experience (Frosch, 2011; Gyekye and Salminen, 2009; Orrù et al., 2019). However, in other sectors such as manufacturing, the impact of the AW is controversial, especially on productivity and other aspects of operational performance (e.g., quality, flexibility, throughput rate). Some studies have shown that, despite the positive aspect of increased experience, the natural decline in physical and physiological functions, including visual ability, musculoskeletal force, flexibility, motion capability, and memory/concentration, negatively affects operational performance (Arena et al., 2022; Börsch-Supan and Weiss, 2016; Kenny et al., 2016; Peruzzini and Pellicciari, 2017). For example, when repetitive movements are required, the reduced strength and joint

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mobility of the AW reduces operational performance as a consequence of tendon and other musculoskeletal disorders (Palmer et al., 2007). More generally, age is considered the human factor that has the highest negative impact on operational performance; for example, the average assembly time of workers increases by 1% every year after the age of 38 (Abubakar and Wang, 2019).

However, the AW not only impacts operational performance, but also affects occupational safety and health (OSH). With the increase in retirement age in many EU member states, the challenges related to prolonging working life, keeping workers healthy, and maintaining their employability and work ability until retirement have emerged and will increase in prominence. Hence, problems related to longer and cumulative exposure to occupational hazards and the presence of chronic health conditions that might affect workers must be considered. For example, cumulative trauma disorders (CTDs), which are related to a reduction in joint mobility, decrease in muscular strength, and slow reaction and movement times (Roper and Yeh, 2007), are one of the most commonly found health risks among the AW which do not affect younger workers. CTDs lead to an increased probability of occupational injuries in workers as they age (Bande and López-Mourelo, 2015; Hasebe and Sakai, 2018). Moreover, the duration and frequency of sick leave increases with age, due to the slower recovery of the AW (Streb and Voelpel, 2009). Furthermore, the impact on OSH is not confined to physiological effects but also includes psychological effects. Mental health problems are reported to be one of the main reasons for sick leave, with the longest duration of absence among workers aged 50 to 59, and the main reasons for mental-health-related absences were anxiety and depression (Coduti et al., 2015). Work stress can also be a cause of mental health absences (Mezuk et al., 2011).

Therefore, it can clearly be seen from current research that companies should consider the AW as an important aspect in the design and management of their operations. Specific interventions for the AW should be considered in any attempts to improve operational and/or OSH performance in the workplace by means of targeted activities and initiatives. So far, most companies have implemented interventions using the same criteria for the AW and younger workers. It is necessary to develop a tool that can assist decision makers in determining the most suitable interventions to develop age-friendly workplaces, both in terms of operations and OSH. This tool should also consider the fact that interventions to improve operational performance also impact OSH performance, and vice versa. For example, in the context of repetitive handling activities, job rotations have recently emerged as an effective practice for improving OSH performance by eliminating or reducing the exposure of workers to health and safety risk factors (Calzavara et al., 2020). However, job rotations can also impact operational performance: by giving workers tasks that better fit their skills and abilities, it is possible to increase productivity as well as ergonomics (Botti et al., 2017). Similarly, training has also been reported to act on both operations and OSH. For example, training programmes for the AW can lead to fewer errors and accidents, which in turn improves both operational and OSH performance (Arena et al., 2020; Börsch-Supan and Weiss, 2016; Truxillo et al., 2015). Moreover, specific training practices for the AW aimed at skill development can further enhance both operational and OSH performance by increasing workers' skills and workers' satisfaction and motivation, respectively (Abubakar and Wang, 2019; Appelbaum et al., 2016a; Roda et al., 2019). In this study, we aim to support companies in considering the AW when designing, implementing, and controlling interventions for manufacturing workers. To do so, we propose a conceptual decision support system (DSS) that enables decision makers to understand the current operational and OSH performance of their workplace and identify the proper interventions that need to be adopted to improve these performances in an AW context. To develop such DSS, it is crucial to identify the operational and OSH Key Performance Indicators (KPIs) affected by the AW, and, to do so, we have carried out a systematic literature review. The systematic literature review serves as a basis for the development of the DSS since it enables to identify not only the operational and OSH Key Performance Indicators (KPIs) affected by the AW, but also the proper interventions that can be adopted by companies to improve operational and/or OSH performance and the interrelations between the different interventions (and hence between operational and OSH KPIs). In this way, we can develop a conceptual DSS that has a strong theoretical background (the different KPIs, the interventions and their interrelations are obtained from a systematic literature review of the existing literature) and that can guarantee a win–win approach: by knowing the interrelations between the interventions and the operational and OSH KPIs, in fact, we can ensure that both the operational and OSH performance are improved at the same time.

Moreover, the conceptual DSS also considers the potentialities provided by the advent of Industry 4.0 (I4.0) technologies. I4.0 technologies can, in fact, have a dual role, by (i) supporting decision makers both in collecting and analysing data and (ii) being included in the interventions themselves. With regards to (i), sensors and big data analytics, for example, enable the collection and analysis of a multitude of data, which is useful for KPI evaluation. Moreover, machine-learning practices can support the identification of the most relevant KPIs for the problem under investigation (Syafrudin et al., 2018). With regards to (ii), I4.0 technologies have been shown to improve both operational and OSH performance (Sgarbossa et al., 2020). For example, the use of a Collaborative robot (cobot), to perform some activities while the operator performs other tasks has been reported to improve the throughput of a system and increases the ergonomics of the assembly line when repetitive and non-ergonomic tasks are assigned to the cobot (Peron et al., 2020). More examples can be found in Lavallière et al. (2016)

The remainder of the paper is structured as follows: In Section 2., we describe the methodology adopted to identify the operational and OSH performance and related interventions in AW context. Specifically, Section 2.1. presents the literature review, Section 2.2. and 2.3. reports the achieved results of the literature review in terms of operational performance and OSH performance, respectively, while in Section 2.4, the intervention in that have been adopted in an AW context to improve operational (Section 2.4.1.) and OSH (Section 2.4.2.) performance and intervention KPIs together with their interrelations with operational and OSH KPIs (Section 2.4.3.) are reported. The conceptual DSS is described in Section 3. while, in Section 4. illustrative simplified case research is depicted to explore the implications of the proposed conceptual DSS in a real-like context. Finally, Section 5 presents the discussion and conclusions.

2. Operational and OSH performance and related interventions in an AW context

The proposed approach involves the development of a conceptual Decision Support System (DSS) that aims at supporting decision makers in designing interventions within an AW context. To do so, we have first identified the aspects of operational and OSH performance affected by the AW by means of a systematic literature review, whose details are reported in Section 2.1. The results of the systematic literature review, then, are reported in Sections 2.2. and 2.3. with respect to operational KPIs and OSH KPIs affected by the AW, respectively. Moreover, Section 2.4. reports the valuable interventions (obtained from the systematic literature review) adopted by companies to improve both operational and OSH performance (Section 2.4.1. and 2.4.2., respectively), also considering the impact that such interventions could have on operational and OSH performance and vice versa (Section 2.4.3.).

2.1. Systematic literature review

To guarantee the correct functionality of the conceptual DSS developed herein, it is fundamental to correctly identify the operational and OSH KPIs affected by the AW and their interrelations. Moreover, an understanding of effective interventions to improve both operational and OSH performance within an AW perspective is also needed. To this end, we carried out a systematic literature review where we investigated the aspects of operational and OSH performance affected by the AW (both negatively and positively) and the interventions that are commonly used to improve operational and/or OSH performance within an AW perspective. It is worth repeating that the literature review provides the foundations for developing the conceptual DSS since it enables to identify (i) the different operational and the OSH performance affected by the AW, (ii) the interventions adopted by companies to improve such performance, and (iii) how an intervention designed to improve a certain performance affects the other (for example, how an intervention designed to improve the operational performance affects the OSH performance), which are all crucial aspects that need to be included in the DSS.

The literature analysis was carried out as described by Tranfield et al. (2003). The first step was to establish the keywords used for paper selection as reported in Table 1. Then, the search queries are generated by using logical operators 'AND' and 'OR' in order to create Boolean keywords combinations '(keyword of group A) AND (keyword of group B OR another keyword of group B)' as reported by Hosseini et al. (2019).

Then, Scopus was selected as the database for the search in which papers were searched automatically. For papers to be included in this study, they must meet the following criteria:

1. Papers limited to journal articles and reviews
2. Papers published in English language
3. Papers published from 2001 to 2020
4. Papers must refer to the subject areas of 'Social sciences', 'Psychology', 'Economics, Econometrics, and Finance', 'Engineering', 'Decision sciences', and 'Business, Management, and Accounting'

Concerning the subject areas, they were chosen in order to consider only the studies dealing with (i) age and the human body (to analyse ergonomic effects), (ii) age and operational performance (e.g., productivity, throughput, quality), and (iii) age and non-quantitative OSH measures (e.g., satisfaction, motivation, commitment). Therefore, once the search was performed in the database using the selected keywords and criteria, a spreadsheet containing all the collected papers with their title, year, source, primary affiliation, abstract, and web address was achieved. In the screening phase, papers were screened by reading their title and abstract aimed at eliminating the ones clearly not related to the analysed topic.

Then, in the eligibility phase, these papers were screened to evaluate their quality concerning quantitative and qualitative aspects after a full-text review. Finally, a total of 120 papers were considered eligible since they are key contributions for this work and, finally, they were included in the analysis. Fig. 1 shows the different steps of the literature search according to the PRISMA protocol (Moher et al., 2010).

These documents were then analysed to identify the relevant operational and OSH KPIs in the AW context (Sections 2.2 and 2.3, respectively), the effective operational and OSH interventions (and related KPIs; Section 2.4.1. and 2.4.2., respectively), and the interrelations between operational, OSH, and intervention KPIs (Section 2.4.3.). To obtain such information is in fact crucial to develop an effective DSS.

Table 1
Search keywords used in the systematic literature review.

Group 1	Group 2	
'ageing work**'	'safety'	'health'
'old work**'	'hazard'	'risk'
'ageing employee'	'accident'	'disease'
'old employee'	'prevent**'	'intervention'
'ageing labo**'	'performance'	'efficien**'
'old labo**'	'productivity'	

2.2. The AW and operational performance

In the literature, some studies have treated the AW as a variable that influences operational performance. Given that the natural decline in physical and physiological functions with ageing result in reduced visual ability, strength, and memory/concentration, and in increased ergonomic issues (Cote et al., 2014; Ilmarinen, 2002; Qin et al., 2014; Truxillo et al., 2012), it is natural to expect a decrease in operational performance among the AW. Varianou-Mikellidou et al. (2020), for example, reported that worker efficiency decreased with age, confirming the results of Pennathur et al. (2003), who reported that the AW are less efficient than younger workers. Moreover, Abubakar and Wang (2019) reported that the average task execution time of workers increased by 1% every year after the age of 38. Similarly, Zwick and Gobel (2011) found that productivity increased until the age of 40 years, and then decreased, in line with the results of Alessandri et al. (2020). This was partially confirmed by Börsch-Supan and Weiss (2016), who evaluated truck assembly lines and reported decreased productivity only among AW with limited experience in the job. Contrarily, they reported that workers who grew old in the plant showed a productivity enhancing effect; accumulated experience compensated for the decline in physical and physiological functions. Specifically, they reported that the productivity profile of individual workers increased until age 65, and they related this to the number and severity of assembly errors. Although the AW were slightly more likely to make errors, they hardly made any severe errors due to their increased experience. Similar results were also found by Roosaar et al. (2019) and Kim (2019), who showed that the AW remained at least as productive as younger workers.

Moreover, the experience of the AW not only represents a factor that enables them to remain productive, but it is also extremely valuable for organisations. According to Massingham (2018), the knowledge loss that follows the retirement of members of the AW affects many aspects of a company if the knowledge has not been transferred to the younger workforce. Specifically, the study reported that knowledge loss led to reduced productivity, strategic misalignment of the workforce (due to capability gaps), resource cuts (due to stakeholders' dissatisfaction with performance), decreased work quantity and quality (due to inexperienced employees), reduced market share (due to customer mistrust), longer time to reach competence (leading to learning costs), high task-execution times, and decreased risk management capacity. Moreover, Guvernator and Landaeta (2020) reported that the retirement of the AW is critical because of technical knowledge losses: the technical knowledge drain generated when experienced operational workers retire negatively affects system operability, increasing the mean time to repair (MTTR) and setup time.

Based on these insights, we were able to identify seven different operational KPIs that were affected by the AW (Table 2). Therefore, those indicators should be taken into consideration to develop the DSS.

2.3. The AW and OSH performance

With chronic health problems becoming more prevalent and workers being exposed to workplace hazards for longer due to increased retirement age, OSH is becoming a fundamental aspect of AW-related issues (Varianou-Mikellidou et al., 2019). Both physical and mental health conditions play an important role in OSH. With regard to physical health, CTDs represent the most common health risks among the AW (Jones et al., 2013; Kowalski-Trakofler et al., 2005; Yang et al., 2020). This is a big issue, especially in assembly, where the AW have to deal with repetitive movements and lifting, lowering, and carrying of moderate to heavy loads, which leads to lumbar, spine, neck, and shoulder symptoms due to the reduction of physical strength and joint mobility (Drake et al., 2017; Landau et al., 2008; Thogersen-Ntoumani et al., 2017). It is thus natural to expect an increase in occupational injuries and accidents among the AW, and this was confirmed by the observations of Hasebe and Sakai (2018), who found an increase in the accident

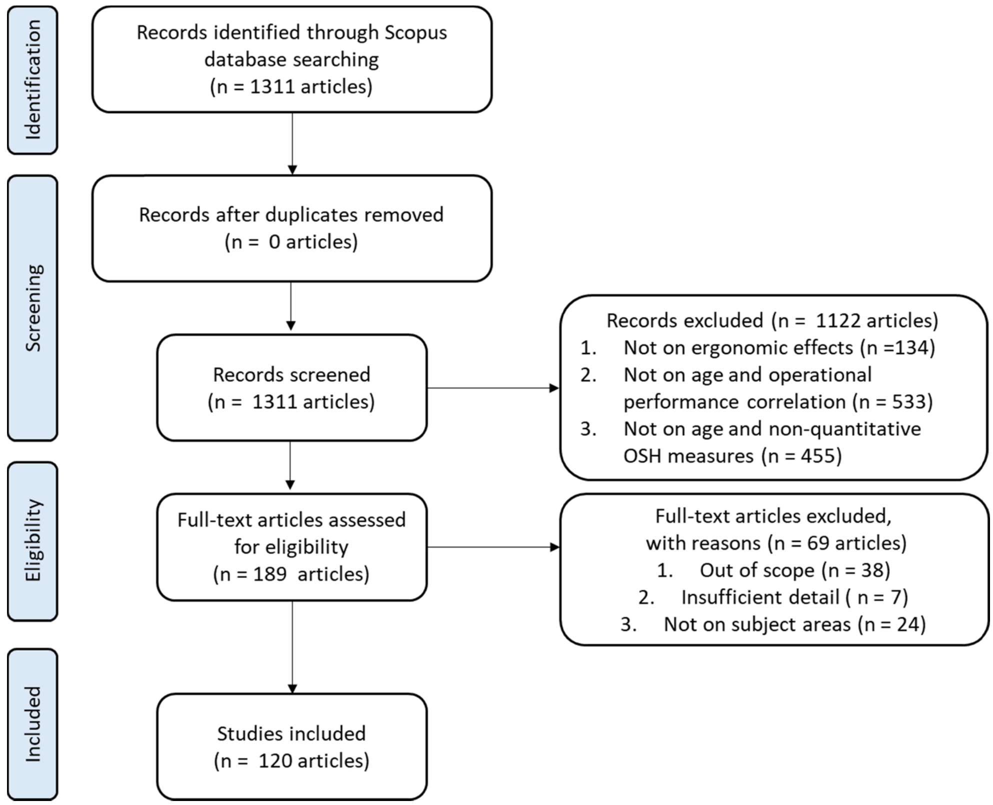

Fig. 1. PRISMA protocol diagram.

Table 2
Operational KPIs affected by the AW.

KPI indicator	Reference
Productivity	(Alessandri et al., 2020; Börsch-Supan and Weiss, 2016; Cote et al., 2014; Goebel and Zwick, 2011; Ilmarinen, 2002; Kim, 2019; Massingham, 2018; Qin et al., 2014; Roosaar et al., 2019; Truxillo et al., 2012)
Task execution time	(Abubakar and Wang, 2019; Massingham, 2018)
Worker efficiency	(Massingham, 2018; Pennathur et al., 2003; Varianou-Mikellidou et al., 2020)
Number of assembly errors	(Börsch-Supan and Weiss, 2016; Kim, 2019; Roosaar et al., 2019)
Severity of assembly errors	(Börsch-Supan and Weiss, 2016; Kim, 2019; Roosaar et al., 2019)
Mean time to repair	(Guvernator IV and Landaeta, 2020)
Setup time	(Guvernator IV and Landaeta, 2020)

frequency rate with each additional year of age. This supports the findings of Bande and López-Mourelo (2015) and Lilley et al. (2018), who concluded that the AW have a higher possibility of suffering severe or fatal accidents. However, these studies contradict the findings of Peng and Chan (2019), who reported that the frequency of accidents decreases with age. Similar results were also obtained by Gyekye and Salminen (2009) and by Kowalski-Trakofler et al. (2005) and Cloutier and Champoux (2000), which can be linked to the increased experience of the AW and their more positive attitudes toward safety (Di Pasquale et al., 2020; Karimi and Taghaddos, 2020; Siu et al., 2003). However, despite reporting a lower frequency of accidents, Peng and Chan (2019) reported that their severity increases with age. This supports the findings of Stoesz et al. (2020) and Bravo et al. (2020), that, compared to younger workers, the incidence of work-related injuries was lower among the AW, but they endured more severe and costly work-related injuries. This can explain the results obtained by Streb and Voelpel (2009), who reported that the duration of sick leave increases with age, confirming the findings of Ringenbach and Jacobs (1995), who reported that the AW experienced more days of injury. Similar results were also reported by Claus et al. (2019) and Fontaneda et al. (2019).

As mentioned earlier, in addition to physical health, OSH performance also has a psychological aspect. Coduti et al. (2015), for example, reported that mental health problems represent one of the main reasons for sick leave, with the longest duration of absence among workers aged 50 to 59. The main reasons for mental health problems are anxiety, work stress, and depression (Laaksonen et al., 2012; Steinert and Haesner, 2019; Sun et al., 2020). Specifically, Henseke (2018) reported job satisfaction, motivation, and workplace climate to be the three main causes of depression, with the latter being particularly influenced by workplace incivility (e.g., being devalued, overlooked, and treated as less capable) and by negative stereotypes about the AW (e.g., they are less willing to attend training and development learning; their productivity declines with age; they cost a lot in terms of wage, health care, and work condition improvement; they are more resistant to changes) (Appelbaum et al., 2016b, 2016c, 2016d; Kleissner and Jahn, 2020; Kunze et al., 2013; Marchiondo et al., 2020; Stegmann et al., 2020). A detailed list of age-related stereotypes can be found in Petery et al. (2020).

From the above, we were able to identify eight OSH KPIs that are affected by the AW (Table 3), which need to be considered in the DSS.

2.4. *The AW and interventions*

In this section, the interventions that have been adopted in an AW context to improve operational (Section 2.4.1.) and OSH (Section 2.4.2.) performance are reported. The identified intervention KPIs are then reported in Section 2.4.3., together with their interrelations with operational and OSH KPIs.

2.4.1. *Operational interventions*

From Section 2.2. it emerged that the main causes for decreased operational performance with increased age are related to declining

Table 3
Occupational safety and health KPIs affected by the AW.

KPI category	KPI indicator	Reference
Quantifiable	Injury claim rate	(Bravo et al., 2020; Stoesz et al., 2020)
	Frequency of accidents	(Cloutier and Champoux, 2000; Di Pasquale et al., 2020; Gyekye and Salminen, 2009; Hasebe and Sakai, 2018; Karimi and Taghaddos, 2020; Kowalski-Trakofler et al., 2005; Peng and Chan, 2019; Siu et al., 2003)
	Severity of accidents	(Bande and López-Mourelo, 2015; Lilley et al., 2018; Peng and Chan, 2019)
	Rate of sick leave	(Claus et al., 2019; Fontaneda et al., 2019; Ringenbach and Jacobs, 1995; Streb and Voelpel, 2009)
Non-quantifiable	% of the AW reporting mental health problems	(Coduti et al., 2015; Laaksonen et al., 2012; Steinert and Haesner, 2019; Sun et al., 2019)
	Workplace climate	(Appelbaum et al., 2016d, 2016b, 2016c; Kleissner and Jahn, 2020; Kunze et al., 2013; Marchiondo et al., 2020; Petery et al., 2020; Stegmann et al., 2020; Varianou-Mikellidou et al., 2019)
	Job satisfaction	(Henseke, 2018)
	Motivation	(Henseke, 2018; Kooij et al., 2013)

physical and physiological functions and to the knowledge loss that follows the retirement of the AW. Interventions have thus focused on mitigating the impact of these factors on operational performance. It has been shown that the decline in physical function can be mitigated by promoting healthy lifestyles (food habits, physical exercises, etc.) and worksite wellness programmes (Poscia et al., 2016; Rožman et al., 2019; Shephard, 2000). In this way, the functional capacity of the AW can be boosted, simplifying the performance of physiologically demanding jobs and increasing their work ability (Malińska and Bugajska, 2021). Another possibility to limit the impact of the decline in physical and physiological functions on operational performance is to adjust the AW to job rotations (Boenzi et al., 2015). In this way, the AW can be given tasks that better fit their skills and abilities (in terms of both physiology and knowledge) (Botti et al., 2017). Alternatively, similar results can be achieved with the use of mixed-age working groups, where younger workers can balance the weaknesses of AW (and vice versa) (Dropkin et al., 2019). Moreover, the use of mixed-age working groups facilitates intra-organizational networking, which is reported to be a key mechanism for knowledge transfer (Van der Heijden et al., 2020). In this way, it is possible to limit the knowledge loss that arises when the AW retire.

Moreover, knowledge loss can be reduced by: (i) increasing the retention rate, (ii) offering additional training, and (iii) improving the workplace. With regards to increasing the retention rate, Stirpe et al. (2018) reported that the retention rate can be increased by acting on HR policies; however, in another study, offering retention measures (e.g., bonuses to the AW) did not have any effect (Midtsundstad and Hermansen, 2019). In terms of HR policies, Stirpe et al. (2018) compared the effect of adopting either high-performance work systems (HPWS) or flexible work systems (FWP) on the AW retention rate, and they reported that FWP programmes had a positive effect, accommodating declines in their cognitive and physical abilities, as well as changes in their priorities. Similar results were also found by Albanese et al. (2020) and Claudon et al. (2020). Albanese et al. (2020) reported that part-time practices prolonged employment for a maximum of four years, while Claudon et al. (2020) reported that flexible pacing during assembly of customised products reduced task execution times.

With regards to offering additional training, Gadomska-Lila (2020) reported that reverse mentoring is an efficient tool for sharing knowledge: the AW can lead training sessions in order to transfer the knowledge and experience they have accumulated to younger workers. Furthermore, the author also reported that reverse mentoring created engagement among the AW, thus also increasing the retention rate. Moreover, training is also beneficial for members of the AW with limited experience in certain tasks. Specifically, Göbel and Zwick (2013) suggested that specific training contents and forms (e.g., more applied and less mentally demanding training) can be more efficient for the AW than for younger workers. Other training strategies can be found in Koc-Menard (2009), and the necessity to customise training for both the AW and younger workers was highlighted by Vilčiauskaitė et al. (2020). However, although training for the AW is an important skill improvement measure, the reality is that companies do not make the same effort as with other age groups, mainly because of negative stereotypes (e.g., unwillingness to learn, poor health conditions, decreased cognitive capacities).

In terms of improving the workplace, Kawakami et al. (2000), in agreement with Mutambudzi et al. (2020), suggested that redesigning workplaces can be an effective way to improve operational performance. Bauer (2020), for example, reported that the development of 'age-friendly' workplaces can improve operational performance. Moreover, Nagarajan et al. (2019) suggested that the development of such 'age-friendly' workplaces can also increase the retention rate. Finally, Göbel and Zwick (2013) reported that the use of specific equipment in workplaces also increases operational performance. This has become very important with the advent of Industry 4.0 (I4.0) technologies. Cobots, for example, can assist workers during assembly and can lead to increased throughput by performing some activities while the workers perform other tasks (Peron et al., 2020). Moreover, augmented and virtual reality can improve training procedures (Ho et al., 2018; Lee et al., 2008). Lavallière et al. (2016), for example, reported how augmented reality could be utilised to show a less experienced worker how a task should be performed.

2.4.2. OSH interventions

With regards to the impact of the AW on OSH performance (Section 2.3.), the literature review revealed that CTDs represent one of the main health risks, especially in assembly lines where the AW are subjected to repetitive movements and lifting/carrying of heavy loads. Many interventions have thus focused on improving the ergonomics of the workplace in such a way that working conditions match the health and functional capacity of the AW (Peng and Chan, 2020). Similar to Ringenbach and Jacobs (1995) and Kooij et al. (2008), Hennekam and Herrbach (2013), suggested improving workplace ergonomics by redesigning workstations. Specifically, when redesigning a workstation, Case et al. (2015) and Porta et al. (2020) highlighted three main aspects that need to be considered: (i) reduction of extreme joint movement, (ii) reduction of excessive force, and (iii) reduction of repetitive tasks. These aspects were then further extended by the work of Battini et al. (2011), who developed a new methodological framework to improve ergonomics in assembly system design where body posture and human diversity are also considered. Moreover, King (2002) reported that, besides the workstation, interventions should also focus on flooring, which can alleviate problems associated with constrained standing. Furthermore, Boenzi et al. (2015) suggested that job rotation is another effective way to smooth the workload and reduce ergonomic risks. This agrees with Botti et al. (2017), who reported that job rotation could reduce ergonomic risk by varying job intensity and required movements. In addition, the recent advent of I4.0 technologies has also been reported to support the improvement of workstation ergonomics. Specifically, Mateus et al. (2019) reported that human-robot collaboration could be an effective solution as it combines the flexibility of humans with the consistency of robots. Fox et al. (2019) showed that the use of exoskeletons can reduce excessive force, while Peron et al. (2020) reported that the use of a cobot for repetitive and non-ergonomic tasks can improve workstation ergonomics. Similarly, tow trains can ease the ergonomic burden on the AW (Diefenbach et al., 2020). Furthermore, other I4.0 technologies can be helpful in improving workstation ergonomics. For example, Battini et al. (2018) and Simonetto et al. (2022)

demonstrated how the use of I4.0 technologies such as virtual reality and motion capture systems could facilitate and improve the redesign of workstations, while Lavallière et al. (2016) reported that the use of wearable devices facilitates the monitoring of health, safety, and well-being, enabling the identification of at-risk situations and, consequently, the modification of the work environment.

Another important aspect that affects OSH performance is mental health, with anxiety, work stress, and depression representing the critical issues. Hence, Truxillo et al. (2015) highlighted the importance of health promotion interventions that aim to increase both the mental and physical health of workers. Given that workers spend most of their time in the workplace, healthy work environments would benefit the mental health of the AW (Gyllensten et al., 2019). Specifically, Truxillo et al. (2015) suggested the use of stress management programmes and active and healthy lifestyle promotion programmes, in agreement with Kurtzer et al. (2020) and Wu and Porell (2000), who also suggested the use of health and wellbeing practices and leisure exercise activities to increase the mental health of the AW. Moreover, Gyekye and Salminen (2009) reported that workplace safety perception impacts the quality of the working environment. Interventions in this context are thus also needed, and Truxillo et al. (2015) reported that redesigning physical aspects of jobs and the use of technology to support the AW are effective in this regard. Moreover, based on the observation that the AW have the most positive and constructive perceptions about workplace safety (Gaudart, 2000; Gyekye and Salminen, 2009), they suggested that the AW should be trained to support and mentor younger colleagues regarding safety. In this way, the AW would feel valued by the company, increasing their motivation and limiting the risk of depression. Alternatively, Naghavi et al. (2019) reported that motivation could be increased by empowering the AW. This is in line with the findings of Rožman et al. (2017), who reported that flexibility, training, autonomy, and good workplace relationships are effective ways to maintain high levels of motivation. Good relationships and training have also been highlighted as important factors to improve motivation (Truxillo et al., 2015). Specifically, they suggested acting on the age diversity climate to improve the AW's motivation. The perception of ageism or age-related stereotypes negatively impact how the AW rate the workplace environment and their relationships in general, which in turn decreases motivation and job satisfaction, impacting mental health (Deng et al., 2020; Fu and Mount, 2002; Zhang and Gibney, 2019). Marchiondo et al. (2019) reported that social policies may reduce age-related stereotypes, while Truxillo et al. (2015) reported the use of intergenerational exposure, team interventions, training of supervisors and teams, and mixed-age working groups as effective solutions to reducing age-related stereotypes. Moreover, in agreement with Greller (2000) and Crane et al. (2020), Kooij et al. (2013) reported that training programmes for the AW can also overcome age-related stereotypes; for example, by expanding the AW's knowledge horizon, skill update initiatives and skill development programmes can overcome the stereotype that the AW cannot advance their careers, and provide opportunities for the pursuit of new career paths. Finally, the last intervention suggested in the literature to improve mental health among the AW is to change working hours (Wels and Takami, 2021). Long working hours can make the AW feel more tired and exhausted, eventually leading to mental health problems (Laaksonen et al., 2012); flexible work arrangements and part-time work have been suggested as possible interventions (Koopman-Boyden and Macdonald, 2003).

2.4.3. Intervention KPIs and their interrelations with operational and OSH KPIs

Sections 2.4.1. and 2.4.2. presented eleven intervention types that are suitable in an AW context (Table 4), together with their corresponding KPIs.

Sections 2.4.1. and 2.4.2. also showed that operational performance interventions might impact OSH performance and vice versa. In the following, we will describe these interrelations (which are schematically

Table 4
Interventions and corresponding KPIs in an AW context

Intervention area	KPI indicator	References
Stress management programmes	Number of stress management programmes	(Kurtzer et al., 2020; Rožman et al., 2017; Truxillo et al., 2015; Wu and Wu, 2000)
Active and healthy lifestyle promotion programmes	Number of active and healthy lifestyle promotion programmes	(Crane et al., 2020; Deng et al., 2020; Edge et al., 2020; Fu and Mount, 2002; Greller, 2000; Gyllensten et al., 2019; Kurtzer et al., 2020; Malińska and Bugajska, 2020; Marchiondo et al., 2019; Naghavi et al., 2019; Peng and Chan, 2020; Poscia et al., 2016; Rožman et al., 2019, 2017; Shephard, 2000; Truxillo et al., 2015; Wu and Wu, 2000; Zhang and Gibney, 2019)
Job rotation	% of the AW involved in job rotation	(Boenzi et al., 2015; Botti et al., 2017)
Mixed-age working groups	% of the AW involved in mixed-age working groups	(Dropkin et al., 2019; Guillén and Kunze, F., 2019; Marchiondo et al., 2019; Truxillo et al., 2015; Van der Heijden et al., 2020)
Training for the AW	% of the AW trained per annum	(Abubakar and Wang, 2019; Appelbaum et al., 2016a; Crane et al., 2020; Gadomska-Lila, 2020; Gaudart, 2000; Greller, 2000; Gyekye and Salminen, 2009; Kooij et al., 2013; Vilčiauskaitė et al., 2020)
Career development training	Number of career development training sessions per annum	(Abubakar and Wang, 2019; Appelbaum et al., 2016a; Crane et al., 2020; Kim, 2002; Kleissner and Jahn, 2020; Kooij et al., 2013; Marchiondo et al., 2020; Rožman et al., 2017; Vignoli et al., 2021)
Training given by the AW	% of training sessions given by the AW per annum	(Ben Hador and Klein, 2019; Crane et al., 2020; Gadomska-Lila, 2020; Gaudart, 2000; Greller, 2000; Gyekye and Salminen, 2009; Kooij et al., 2013; Nivalainen, 2020; Truxillo et al., 2015)
Physically related workplace improvements	Number of physically related workplace improvements	(Battini et al., 2011; Case et al., 2015; Hennekam and Herrbach, 2013; King, 2002; Kooij et al., 2008; Koopman-Boyden and Macdonald, 2003; Laaksonen et al., 2012; Porta et al., 2020; Ringenbach and Jacobs, 1995; Truxillo et al., 2015; Wels and Takami, 2020)
Psychologically related workplace improvements	Number of psychologically related workplace improvements	(Deng et al., 2020; Fu and Mount, 2002; Gaudart, 2000; Gyekye and Salminen, 2009; Gyllensten et al., 2019; Malińska and Bugajska, 2020; Marchiondo et al., 2019; Naghavi et al., 2019; Rožman et al., 2017; Truxillo et al., 2015; Zhang and Gibney, 2019)
Assistive technologies	% of the AW helped by assistive technologies	(Battini et al., 2018; Diefenbach et al., 2020; Fox et al., 2019; Ho et al., 2018;

(*continued on next page*)

Table 4 (*continued*)

Intervention area	KPI indicator	References
		Lavallière et al., 2016; Lee et al., 2008; Mateus et al., 2019; Peron et al., 2020; Simonetto et al., 2022; Truxillo et al., 2015)
Part-time working practices	% of the AW working part-time	(Albanese et al., 2020; Claudon et al., 2020; Koopman-Boyden and Macdonald, 2003; Laaksonen et al., 2012; Stirpe et al., 2018; Wels and Takami, 2020)

summarised in Table 5), so that decision makers can choose the intervention(s) that improve both operational and OSH performance, guaranteeing a win–win approach.

Stress management and active and healthy lifestyle promotion programmes can be grouped as health promotion interventions. Stress management programmes have mainly been used to improve OSH performance: they have been reported to increase the mental health of the AW by improving their satisfaction and motivation (Truxillo et al., 2015). In addition, better mental health will also impact operational performance (productivity, worker efficiency, main time to repair, and setup time) because it is reported to reduce absenteeism and increase the retention rate (Edge et al., 2021). Healthy lifestyle promotion programmes have mainly been used to mitigate the decline in physical functions, allowing workers to more easily perform physiologically demanding jobs (and hence improve productivity, task execution time, and worker efficiency) (Malińska and Bugajska, 2021; Poscia et al., 2016). This has also been reported to increase the mental health of AWs and their job satisfaction (Crane et al., 2020; Gyllensten et al., 2019; Kurtzer et al., 2020; Wu and Porell (2000)).

Job rotation has been reported to impact both operational and OSH performance (Botti et al., 2017): by giving the AW tasks that better fit their skills and abilities (both physically and in terms of knowledge), it is possible to both reduce ergonomic risk and improve operational performance (especially through productivity, task execution time, and AW efficiency, but also number and severity of errors).

Mixed-age working groups, which facilitate knowledge transfer and enable younger employees to balance the weaknesses of the AW and vice versa, have been primarily used as an intervention to improve operational performance (Dropkin et al., 2019; Guillén and Kunze, 2019; Van der Heijden et al., 2020). However, they may also affect OSH performance. On the one hand, mixed-age working groups could favour positive intergenerational exposure, thus increasing job satisfaction among older employees who feel more involved in the company (Marchiondo et al., 2019; Truxillo et al., 2015). Moreover, younger workers could also realise that the common beliefs about the AW (i.e., age-related stereotypes) are not true. On the other hand, younger workers could be carriers of such stereotypes, thus negatively impacting OSH performance (Kleissner and Jahn, 2020; Marchiondo et al., 2020). How the AW interact with younger workers will significantly affect the retention rate: if perceptions of age-related stereotypes are low, the desire to work longer will increase (Abubakar and Wang, 2019; Appelbaum et al., 2016a; Rožman et al., 2017; Vignoli et al., 2021).

Another important intervention that emerged was the training of the AW, which has mainly been considered from the operational performance perspective. Specifically, training can be used to improve the skills of the AW, leading to an increase in productivity and throughput rates due to, for example, increased worker efficiency and reduced rework ratio (Abubakar and Wang, 2019; Appelbaum et al., 2016a). Moreover, the AW could be trained with respect to OSH, leading to a reduction in injuries and accidents and, consequently, of sick leave. Moreover, training can further affect OSH performance. On the one hand, it could increase the AW's motivation, making them feel that they are still important for the organisation (Crane et al., 2020; Greller, 2000; Kooij et al., 2013); on the other hand, it could also negatively impact OSH performance: if different training programmes are given to younger workers and the AW, this could increase the AW's perception of

Table 5
Interrelations between interventions and operational and OSH performance.

Interventions	Operational KPIs							OSH KPIs							
	Productivity	Task execution time	Worker efficiency	Number of assembly errors	Severity of assembly errors	Mean time to repair	Setup time	Injury claim rate	Frequency of accidents	Severity of accidents	Rate of sick leave	% reporting mental health problems reported	Workplace climate	Job satisfaction	Motivation
Stress management programmes	▲	=	▲	=	=	▼	▼	=	=	=	▲	▲▲	=	▲▲	▲▲
Active and healthy lifestyle promotion programmes	▲	▼	▲	=	=	=	=	=	=	=	▼	▼	=	▲	=
Job rotation	▲▲	▼▼	▲▲	▼	▼	=	=	=	=	=	▼▼	=	=	=	=
Mixed-age working groups	▲▲	▼▼	▲▲	▼	▼	▼	▼	▼	▼	▼	△▽	△▽	△▽	△▽	△▽
Training for the AW	▲▲	▼▼	▲▲	▼▼	▼▼	▼▼	▼▼	▼▼	▼▼	▼▼	▼	△▽	△▽	△▽	△▽
Career development training	▲	▼	▲	=	=	=	=	=	=	=	▼▼	▼▼	=	▲▲	▲▲
Training given by the AW	▲	▼	▲	=	=	=	▼▼	▼▼	▼▼	▼▼	▼▼	▼▼	▲	▲	▲▲
Physically related workplace improvements	▲▲	▼▼	▲	=	=	=	▼▼	▼▼	▼▼	▼▼	▼▼	=	=	=	=
Psychologically related workplace improvements	▲	▼	▲	=	=	▼	▼	=	=	=	▼	▼▼	▲▲	▲▲	▲
Assistive technologies	▲▲	▼▼	▲▲	▼▼	▼▼	▼	▼	=	=	=	▼▼	=	=	=	=
Part-time working practices	△▽	▼	▲	=	=	=	=	=	=	=	▼▼	▼▼	=	▲	▲▲

Note: ▲▲ = high performance increase; ▲ = partial increase; = = no impact; ▼▼ = high performance decrease; ▼ = partial decrease; △▽ = uncertain impact (the intervention depends on company-specific variables).

stereotypes (Vilčiauskaitė et al., 2020).

In this regard, career development training plays an important role. The AW frequently suffer from the stereotype that they are unable to achieve career advancement (Crane et al., 2020; Kooij et al., 2013). By carrying out career development training, companies can overcome this perception, thus increasing the AW's motivation and job satisfaction, and hence mental health (Kim, 2002). Moreover, as already described, when the AW are highly motivated and satisfied, they perform better, thus improving productivity and reducing task execution times (Greller, 2000).

It has emerged that reverse mentoring is an effective intervention for both operational and OSH performance. With regards to operational performance, reverse mentoring reduces the impact of knowledge loss. By leading training sessions, the AW can transfer their accumulated knowledge and experience to younger workers (Gadomska-Lila, 2020), as well as improve the workplace climate. In terms of OSH performance, reverse mentoring has an impact in two ways. First, since the AW have a higher safety perception, they can support and mentor younger colleagues regarding safety (Gaudart, 2000; Gyekye and Salminen, 2009). This would result in the AW feeling important for and involved in the company, hence increasing their motivation and mental health. Moreover, as already highlighted above, if the AW feel more important and involved in the company, they are more willing to postpone retirement (Ben Hador and Klein, 2019; Nivalainen, 2020).

Workplace improvements are another important intervention, which can be divided into physically and psychologically related workplace improvements. Physically related workplace improvements (e.g., workstation and flooring redesign) can impact both operational and OSH performance. Effective assembly system layout and workplace design has been reported to improve productivity, worker efficiency, task execution times, and ergonomic risks (Battini et al., 2011). Psychologically related workplace improvements are mainly related to OSH performance, and they mainly focus on limiting ageism and age-related stereotypes (Truxillo et al., 2015). In this way, it is possible to improve mental health, acting on motivation, job satisfaction, and especially workplace climate (Deng et al., 2020; Fu and Mount, 2002; Zhang and Gibney, 2019). Again, an improvement in mental health and workplace climate would also result in improvements in AW efficiency and retention rates.

The use of assistive technology in workplaces has been mainly used as an intervention to improve operational performance. For example, augmented reality can be utilized to improve training procedures, as well as to assist workers in performing their activities (Lavallière et al., 2016; Mourtzis et al., 2019). Similarly, cobots can assist workers during assembly and perform some activities while the workers perform other tasks (Peron et al., 2020). Cobots can also improve OSH performance when they are assigned repetitive and non-ergonomic tasks (Busch et al., 2017; Peron et al., 2020). Additionally, other assistive technologies, such as exoskeletons, have been specifically designed to improve ergonomics. It is worth mentioning, however, that exoskeletons might reduce the AW's flexibility, thus potentially reducing operational performance (Fox et al., 2019).

Finally, the adoption of part-time working schedules for AWs is something that has been considered as an intervention to improve OSH performance. Reduced working times have been reported to improve the mental health of workers (Laaksonen et al., 2012; Truxillo et al., 2015). However, this also impacts operational performance, though its effect is controversial: although working part-time increases worker efficiency, companies need more resources to cover the remaining hours.

3. Conceptual decision support system (DSS)

The conceptual DSS herein developed aims to assist decision makers in understanding the current operational and OSH performance of their workplace and recognising the proper interventions to improve them for the AW context. Specifically, by considering the interrelations between operational, OSH, and intervention KPIs, the conceptual DSS guarantees a win–win approach, where both operational and OSH performance are improved simultaneously by choosing the proper intervention. As reported in Fig. 2, the conceptual DSS consists of four phases: (i) problem statement, (ii) data selection, (iii) data assessment, and (iv) intervention strategy design, implementation, and control. It also considers the potential impact of I4.0 technologies with respect to the three phases of data selection, assessment, and intervention.

3.1. Problem statement

The first phase of the DSS establishes the problem context by defining the company's strategic requirements and operational objectives, as well as the AW scenario (i.e., AW as a proportion of total workforce, tasks executed by the AW). The inputs in this phase (P.I.1 in Fig. 3) are the company's strategic objectives (i.e., the long-term organisational goals), operational objectives (i.e., daily, weekly, or monthly project benchmarks that deliver the larger strategic objectives), and the AW characteristics. The output (P.O.1 in Fig. 3) is the AS-IS configuration of the current scenario (i.e., the problem context) and the desired performance outcomes, which can be used at the beginning of Phase 4 to compare the real and desired status of the AS-IS situation.

P.I.1 are the inputs (i.e., strategic and operational objectives, limitations, and AW scenario in the organisation) and P.O.1 are the outputs (AS-IS configuration of the current scenario and desired performance).

3.2. Data collection

This phase of the DSS deals with the collection of the data required to achieve the organisation's strategic and operational objectives and consists of the selection of operational and OSH KPIs (Fig. 4). Here, the decision makers could use the operational and OSH KPIs identified herein (Sections 2.2. and 2.3., respectively). Specifically, I4.0 technologies can be of help in the selection of relevant operational and OSH KPIs because, based on historical data, they can, for example, suggest the operational and OSH KPIs that are most suitable for the problem context identified in the previous phase. The decision maker can then add or remove the suggested operational and OSH KPIs according to their requirements.

D.I.1 is the list of all the KPIs identified in this study based on the literature review, and D.O.1 is the final set of selected KPIs based on the problem context identified in the previous step.

3.3. Data assessment

The third phase of the conceptual DSS deals with data assessment, i.e., the calculation of the selected operational and OSH KPIs. In this way, decision makers will be supported in determining the relevant interventions in accordance with the problem context and the desired performance outcomes identified in phase one. Moreover, in this phase, decision makers will be able to assign relative weights to operational and OSH KPIs based on their relevance with respect to the identified problem. This will be of help in determining (in the next phase) the most suitable intervention(s) by considering the interrelations between interventions and operational and OSH KPIs (Table 3). In this phase, I4.0 technologies could be useful, especially machine learning algorithms that can suggest amended weights based on historical performance data. The detailed steps of phase three are shown in Fig. 5.

A.I.1 is the final set of KPIs to be analysed for the problem; A.O.1 is the final set of KPIs with corresponding scores, then translated into A.I.2; and A.O.2 is the final set of KPIs with related scores (A.I.2) and the definition of related weights.

3.4. Intervention strategies

The final component of the decision-making process encompasses

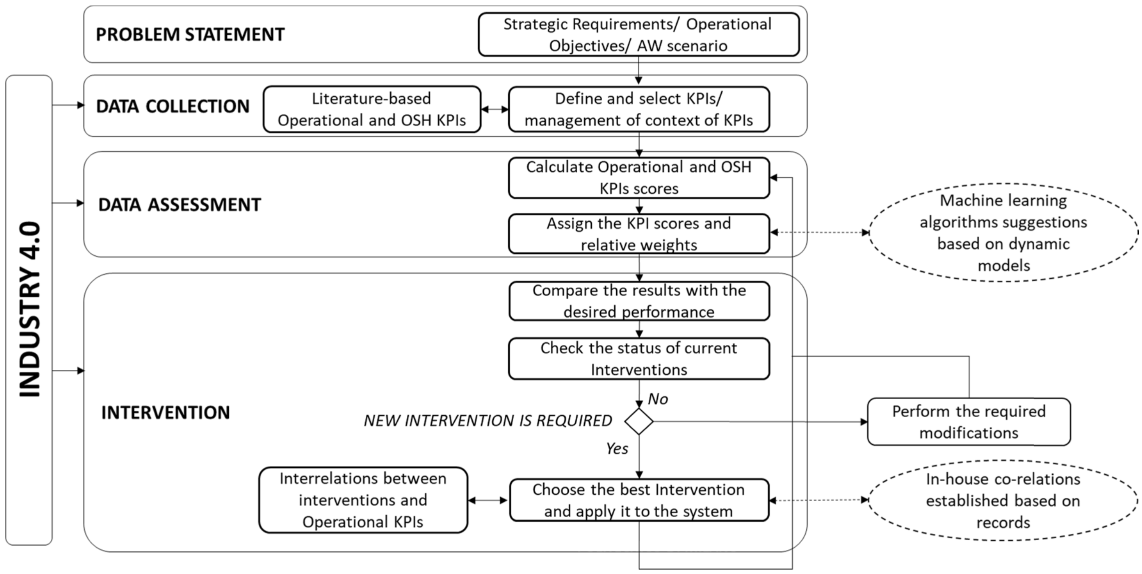

Fig. 2. Basic structure of the conceptual DSS.

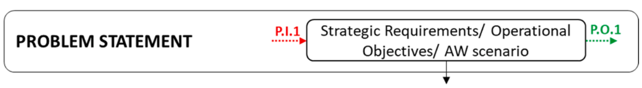

Fig. 3. Phase 1: Problem statement.

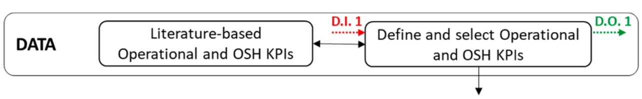

Fig. 4. Phase 2: Data collection.

the process of selecting the optimal intervention for the defined problem statement. The scores from the *data assessment* step are here compared with the desired performance outcomes identified in phase one. Subsequently, the decision maker will check the current performances of the interventions which are in place (leveraging the intervention KPIs herein defined or intervention KPIs more suitable to the specific case under consideration). Specifically, based on the current performance of the interventions in place, decision makers can assess whether new interventions are needed. If the performance of the interventions in place is unsatisfactory but can be amended, the current interventions are modified and improved, and the decision loop stems back to A.I.1; otherwise, decision makers select a new intervention strategy, possibly consisting of a set of interventions. In this phase, the decision maker must consider the interrelations between the interventions and the operational and OSH KPIs. Here, decision makers can refer to the KPI interrelations described in Table 3 as an initial reference for determining qualitatively the existing interrelations, for then quantify them through in-house measures in order to optimize the interventions. Additionally, I4.0 technologies such as in-house machine learning algorithms could be beneficial because they can propose interventions suitable for the required improvements. However, decision makers have the discretion to add or remove the proposed interventions. The decision loop is finally closed with the *data assessment* phase to run the new calculation (step A.I.1) after imposing the new interventions. The detailed steps of phase four are shown in Fig. 6.

IN.I.1 represents the scores of KPIs (from A.O.2); IN.O.1 and IN.I.2 are the comparison between the scores of the KPIs and the desired performance outcomes; IN.O.2 represents information on whether current interventions are performing satisfactorily; IN.I.3 represents the possible modification strategies for the current interventions in place, if needed; IN.O.3 is the modification of current interventions in place when needed; IN.I.4 are the different possible interventions that can be adopted given the problem context and the interrelations with operational and OSH KPIs; and IN.O.4 represents the decision regarding the intervention(s) to be adopted and its (their) application.

4. Illustrative simplified DSS application

An illustrative simplified case research (Yin, 2009) is reported, to explore the implications of the proposed conceptual DSS in a real-like context aiming at providing a clear explanation of how its adoption can take place in practice. Particularly, it refers to an assembly company "C", headquartered in the northern part of Italy, employing 150 workers at a shopfloor level. Company "C" is characterized by the overall ageing of its operators, as most of them are soon approaching retirement or are planning their transition into retirement. Therefore, Company "C" is trying to cope with AW issues with the aim of understanding how older workers can be supported and involved in the assembly system so that they can properly perform their tasks. To this purpose, one of the improvements that Company "C" is implementing, concerns the adoption of interventions to develop age-friendly workplaces without – however – extracting information related to their impact on productivity and other aspects of operational performance (e.g., quality, flexibility, throughput rate). Thus, a decision was made by Company "C": to analyse the potential interventions leveraging a systemic approach based on the

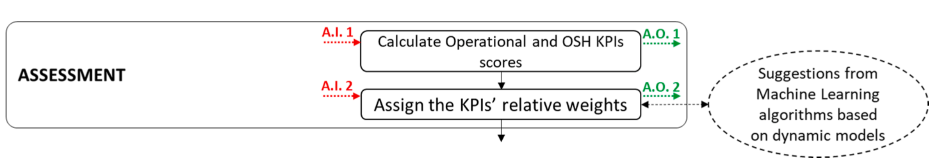

Fig. 5. Phase 3: Data assessment.

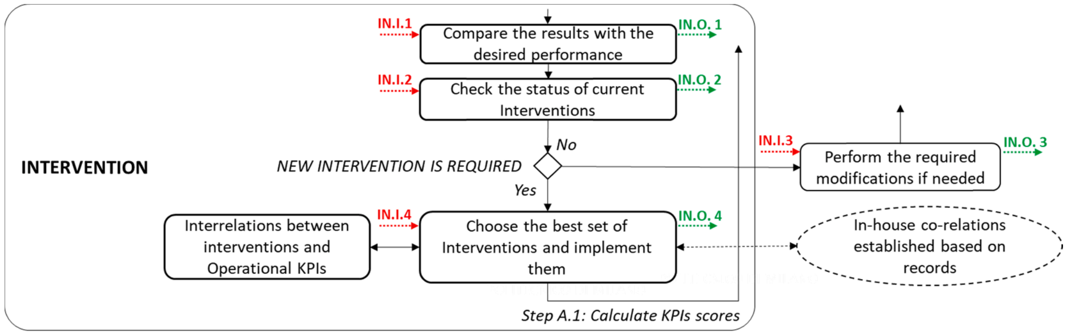

Fig. 6. Phase 4: Intervention strategies.

proposed DSS, in the scope of discovering new information and build knowledge and use this knowledge to define the proper interrelation of these aspects to improve both operators' working conditions and the operative performance.

The goal of this Section is to demonstrate the characteristics of the DSS by replicating, in the setting of an illustrative case company, the steps previously described. There is no need for validation, given its deductive origin. Thus, the main elements in the design of this illustrative case cover the problem statement, data collection and assessment, and, finally, the interventions strategies to be implemented.

4.1. Problem statement

Company "C" targets an increase of competitiveness over a 5 years' period thanks to an overall decrease of costs per assembled unit. Specifically, company "C" aims to improve the assembly pace of a peculiar (and very hard to re-work) assembly system 'AS', by also reducing the maximum number of assembly errors per shift per worker, also in case of AW. The assembly line for 'AS' consists of 20 balanced stations (just installed, high CAPEX and an expected Pay Back Time around 5 years), and it is important that the 20 workers perform their tasks correctly and within the defined time to ensure the required pace, of course not to detriment to OHS conditions. In addition, company 'C' traditionally makes extensive use of job rotation, not already implemented in the assembly line under consideration, which would require the 20 workers to be possibly able to switch when appropriate. Among these 20 workers, 3 are currently AW; in 5 years 10 are expected to be AW among the 20. All in all, a couple of operational performance aspects are triggering the decision makers to identify appropriate strategies, given the amount of AW and the very likely interrelation of these operational performance aspects with OSH performance aspect ion an AW context.

The input in this phase is P.I.1 (see Fig. 3) that involves the company's strategic and operational objective and the AW characteristics, while the output is the P.O.1 (Fig. 3) representing the problem context and the desired performance outcomes. Particularly, input and output are defined as:

P.I.1: Reference area of the company 'C': line 'AS'; increase of efficiency to bring cost reduction; marginal CAPEX investments; increasing portion of AW to be part of this process

P.O.1: higher assembly pace (e.g., considering as a long-term target: average cycle time = 41 s), reduced assembly errors (e.g., considering as a long-term target: average number of errors every two weeks = 1,5 events) and reduced frequency of accidents (e.g., considering as a long-term target: average number of accidents every two weeks = 0,02 events); no opportunity for line 'AS' re-design; 20 workers for 20 balanced stations; increasing portion of AW in the assembly line

4.2. Data collection

Building on the description of the case, on the problem statement phase, on the (prospective, if needed) availability of I4.0 solutions, and on the outcomes of the literature review, the input D.I.1 and the output D.O.1 (see Fig. 4) can be described as follows:

D.I.1: operational and OSH KPIs from Table 3; of course, these KPIs come from a review of the literature, and should not limit the decision makers

D.O.1: selected operational KPIs (Task execution time; Number of assembly errors) and selected OSH KPIs (Frequency of accidents); in this specific case, we assume that the three selected KPIs are already – or will soon, with minor changes – recorded efficiently and with satisfactory frequency by means of appropriate technological solutions.

4.3. Data assessment

The KPIs are assessed based on the recorded data mentioned above. Of course, each of the calculation will be complemented by data about, for example, the specific assembly station and the age of the worker, so as to enable later elaboration; in this specific case, OSH performance is matched univocally with the 'Frequency of accidents', whilst the operational performance is twofold, encompassing both 'Task execution time' and 'Number of assembly errors'. Thus, in the view of optimisation algorithms, led by the knowledge of the specific context, decision makers will assign different weights to:

- 'Task execution time' vs. 'Number of assembly errors'; in this specific example, weights can be set equal to 0,5 both, so as to produce a unique operational performance indicator;
- Operational performance vs. OSH performance; in this specific example, weights can be set equal to 0,5 both, so as to produce a unique performance indicator; the idea is, indeed, to maximize the overall performance indicator, to avoid win-lose decisions.

These weights can be changed using machine learning algorithms, which may take into account for example the impact of each 'event' (i.e., different execution time, assembly error, accident) on some higher-level aspects of performance (i.e., business continuity).

Building on the problem statement phase, on the data collection phase, and on the specific knowledge of the case, A.I.1, A.O.1, A.I.2, and A.O.2 (see Fig. 5) can be derived as follows:

A.I.1: selected operational KPIs (Task execution time; Number of assembly errors) and selected OSH KPIs (Frequency of accidents) from data collection phase

A.O.1: measure of the selected operational KPIs (Task execution time; Number of assembly errors) and selected OSH KPIs (Frequency of accidents); e.g., *in a time period of 2 weeks, Task execution time = (46,4 s; 45,3 s; [...] for the 20 assembly stations), Number of assembly errors = (3 events; 2 events; [...] for the 20 assembly stations), Frequency of accidents = (0 events; 1 events; [...] for the 20 assembly stations)*

A.I.2 = A.O.1

A.O.2: A.I.2 + assignment of the weights to operational KPIs (Task execution time; Number of assembly errors) and selected OSH KPIs (Frequency of accidents) based on their relevance with respect to the identified *problem (0,5 and 0,5).*

4.4. Intervention strategies

Building on the previous phases of the DSS, the operational and OSH KPIs should be compared with the desired performance outcomes identified in phase one, and transformed into scores, e.g., by considering the target 'Task execution time' and target 'Number of assembly errors', then considering the ratio between the current (measured) KPIs and the target ones or vice-versa (as in the case of 'Frequency of accidents'). In this specific case, we have a ratio for the Task execution time KPI, the number of assembly errors KPI and the frequency of accidents KPI equal to 0,78, 0,84, and 0,59, respectively, leading to a comprehensive performance indicator of 0,70 (derived through the weights of the KPIs defined in phase three). In this step, the comparison lies in evaluating how acceptably far are the performance indicators from value '1'. Assuming that the performance indicator is not satisfactory, and that no intervention is already in place to be amended/improved, this example offers room for thoughts regarding the selection of the possible interventions (and further research).

Specifically, the selection of the intervention (or set of interventions) should rely on the interrelations among them and the operational and OSH performance; thus, Table 5 can serve as a reference and a starting line in terms of "qualitative" correlations, when possible supplemented by in-house measures of correlations to make more and more reliable the fine-tuning of the interventions (e.g., when referring to 'Job rotation': how often and how many tasks/stations?) and the forecast of their impact (e.g., using machine learning so as to predict which will be the impact of a defined 'Job rotation' intervention over the KPI 'Number of assembly errors'). What is immediately clear from Table 5 is that, in this specific case, 'Job rotation', even being favoured by the Company "C", would not be appropriate as a stand-alone intervention, because of its negligible positive impact on the OSH performance. In this case, focusing on the three KPIs under investigation, 'Training for the AW' would be preferable, or at least to be implemented jointly, whilst for example 'Physically related workplace improvements' are expected not to have the desired impact on the 'Number of assembly errors'.

Of course, the proposal of the most appropriate intervention strategy can be supported by technology; yet this illustrative example is not aimed at shedding light over the I4.0 technologies, thus the details about what specific technology should be used, or what algorithms should be implemented are not reported; rather, the example is aimed at showing that the knowledge of the specific simultaneous needs in terms of operational and OSH performance, together with the knowledge about the effect of potential interventions on both, can be systematically used to identify and put in place win–win interventions or set of interventions.

IN.I.1 = A.O.2

IN.O.1: 0,78, 0,84, and 0,59 as ratios for the Task execution time KPI, the number of assembly errors KPI and the frequency of accidents KPI, respectively, and 0,70 as comprehensive performance indicator, which is not satisfactory in the short-term

IN.I.2 = IN.O.1

IN.O.2: no intervention already in place to be amended/improved [no need for IN.I.3 and IN.O.3]

→ IN.I.4: Table 5, supplemented by in-house interrelations based on records

→ IN.O.4: (for example) select and implement 'Job rotation' + 'Physically related workplace improvements' (only in case of marginal CAPEX, as expressed in the problem statement phase) OR 'Training for the AW'

5. Discussion and conclusions

In this paper, for the first time to the best of the authors' knowledge, we have developed a conceptual Decision Support System (DSS) that supports decision makers in the choice of the most suitable interventions when companies have to deal with AW issues. Specifically, the conceptual DSS herein developed guarantees a win–win approach where both the operational and OSH performances are improved at the same time, and this is possible thanks to the identification from a systematic literature review of the operational and OSH performance affected by the AW, of the possible interventions, and of the interrelations between the possible interventions and the operational and OSH performance.

Therefore, the conceptual DSS stems from a systematic literature review, which resulted in four significant outcomes for the development of the DSS:

- Identification and discussion of the main aspects of operational performance affected by the AW (i.e., productivity, task execution time, worker efficiency, severity and frequency of assembly errors, mean time to repair, and setup time);
- Identification and discussion of the main aspects of OSH performance affected by the AW (i.e., injury claim rate, frequency and severity of accidents, rate of sick leave, % of mental health problem reported, workplace climate, job satisfaction, and motivation);
- Identification and discussion of the main interventions adopted to improve the operational and OSH performance (i.e., stress management programs, active and healthy lifestyle promotion programs, job rotation, mixed age working group, training for AW, career development training, training given by AW, physically and psychologically related workplace improvements, assistive technologies, and part-time working practices);
- Identification and discussion of the interrelations between the possible interventions and the operational and OSH performance.

The conceptual DSS herein developed builds upon the above-mentioned outcomes since it includes them. The conceptual DSS, in fact, consists of 4 phases, i.e., (i) problem statement, (ii) data selection, (iii) data assessment, and (iv) intervention strategies design, implementation, and control, and the results of the literature review are explicitly considered in the last three phases. Starting from few simple input data (i.e., the strategic and operational objectives of the company and the details of the AW scenario in the company), the conceptual DSS helps in a relatively straightforward way to identify the most suitable intervention strategy(s) to be adopted in an AW context, considering both operational and OSH performance. Moreover, the conceptual DSS formally enables decision makers to consider the possibilities provided by Industry 4.0 technologies in terms of data selection, data assessment, and intervention strategies design, implementation, and control.

The main strength of the herein developed conceptual DSS is represented by the fact that the DSS can guarantee a win–win approach: by knowing the interrelations between the interventions and the operational and OSH KPIs identified from the systematic literature review, in fact, it is possible to ensure that both the operational and OSH performance are improved at the same time. Moreover, the DSS forces to consider together the operational performance and the OSH performance, which are usually treated separately, and to include the effects that interventions designed for one performance has also on the other performance (for example, how an intervention designed to improve the operational performance affects the OSH performance).

The application of the proposed DSS to an illustrative application case is to be considered a replication of its use in a real-like context, to better clarify how to use such DSS. There was no need for validation, given its deductive origin; yet, this illustrative application shows how relatively easily the DSS can be implemented, once the operational performance affected by AW, OSH performance affected by AW, interventions, and their interrelations are available. Indeed, starting from the definition of the strategic and operational objectives and the details of the existing AW scenario, the conceptual DSS properly and easily drives towards the identification and the adoption of the most suitable intervention strategy based on the accurate analysis of the interrelations existing between the operational and OSH performance and the potential intervention selected.

However, although this work finds that the application of the proposed conceptual DSS to an illustrative case study provided promising and interesting outcomes, clearly its use in a real industrial application could be more beneficial to validate it from a practical point of view. Therefore, future research on this aspect is still necessary. In addition, further studies on operational and OSH performance aspects affected by AW are also needed, with the specific angle of industrial/management engineering rather than medicine, as well as more studies on the interrelations between the interventions and the operational and OSH performance. Moreover, given that the impact of I4.0 is quickly becoming crucial, specific studies to understand its impact on operational and OSH performance are also needed.

CRediT authorship contribution statement

Mirco Peron: Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Simone Arena:** Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Guido Jacopo Luca Micheli:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Fabio Sgarbossa:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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