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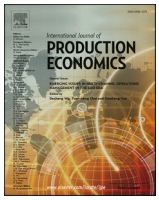

Never too late to learn: Unlocking the potential of aging workforce in manufacturing and service industries

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ABSTRACT

This study systematically reviews 51 articles from Scopus and Web of Science databases to investigate the learning of aging workers in the manufacturing and service industries. It focuses on three key research questions: factors influencing learning among aging workers, effective learning approaches for this demographic, and strategies for enhancing their learning outcomes. The factors influencing learning were categorized into individual, organizational, and societal dimensions, illustrating the sophisticated interaction that shapes the learning environment. Effective learning approaches identified include lifelong learning, utilizing technology, and intergenerational learning, which are interrelated and reinforce each other. Furthermore, we propose a seven-step socio-technical system approach to enhance learning for the aging workforce. This novel approach considers technological tools, as well as human, organizational, and societal elements that play an essential role in the learning process. Our findings present a comprehensive perspective on the complexities of older workers' learning and offer actionable insights to enhance their learning experience. The proposed socio-technical model contributes to creating an inclusive and supportive learning environment, aiming to boost key areas, such as job performance, satisfaction, health, and well-being. This study's implications extend to organizations aiming to optimize the potential of an aging workforce in a rapidly evolving digital world.

1. Introduction

The populations of most developed countries are aging owing to low fertility rates, resulting in zero or negative population growth in Eastern Asia, Europe, Northern America, Australia, and New Zealand (United Nations, 2022). Eurostat (2023) reported that in 2022, approximately 50% of the population of the European Union was older than 44.4 years. Moreover, the Organisation for Economic Co-operation and Development (OECD) highlighted that in its member countries, workers aged 55–64 formed a significant percentage (approximately 65%) of the workforce, with a considerable proportion willing to work past the normal retirement age (OECD, 2019, 2023). Financial considerations, changes in retirement policies, and the desire for continued engagement and fulfillment through work affect these prolonged retirement decisions (Crandall et al., 2022). Defining an "older worker" is a complex task due to the diversity of perspectives and contexts. Age cutoffs for this category can range from 40 to 65 years, influenced by factors such as policy, industry standards, and physical capabilities. This term refers to biological age and encompasses psychological, as well as cognitive aspects (Czaja et al., 2020). Different studies use varying age brackets to classify older workers. For example, Pfrombeck et al. (2023) categorized workers under 35 years as younger and those above 45 or 50 as older. Conversely, Wrobel-Lachowska et al. (2018) employed the term "mature workers" to describe individuals over 55 years of age. Notably, in the literature, the terms "older worker" and "aging worker" are often used interchangeably to describe this segment of the workforce.

Meanwhile, Industry 4.0 (I4.0) introduced and integrated various technologies into the workplace, creating a significant shift in how to approach tasks (Dornelles et al., 2022; Grosse et al., 2023). Although these technologies can make processes more efficient and effective, human characteristics, like flexibility and creativity, are still important (Wolf et al., 2018; Alves et al., 2022). This could explain the growing

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need for workers, regardless of age, to have the necessary skills and knowledge to adapt to the changing technological landscape. Continuous learning and frequent training are crucial for workers to understand and leverage these technologies to enhance productivity and efficiency and remain competitive. Consequently, the successful implementation of I4.0 needs to address the demographic changes to optimize the potential of the aging workforce and leverage technology advances to thrive in this digital era.

In addition to physiological changes, aging also changes human perceptual, mental, and psychosocial abilities (Ilmarinen, 2001). Cognitive aging may diminish humans' thinking, learning, reasoning, decision-making, and memory abilities, affecting workers' productivity and work quality (Digiesi et al., 2020; Hall et al., 2022). These findings translate to negative beliefs about older workers' ability to learn and adapt to new technologies, with some workers also expressing fear, anxiety, reluctance, and low confidence (Kadefors and Hanse, 2012). Although older workers may struggle to keep their learning pace in an I4.0 environment, some researchers suggested that their accumulated experience somewhat offsets their cognitive limitations (Nunes and Kramer, 2009; Hall et al., 2022).

The workforce today comprises workers from four generations: Baby Boomers (born between 1946 and 1964), Generation X (born between 1965 and 1980), Millennials or Generation Y (born between 1981 and 1995), and Generation Z (born between 1996 and 2012) (Salopek, 2000; Ropes, 2013). Each generation possesses distinct characteristics, shaped by their individual life experiences and the environment in which they were raised (Ropes, 2013). Moreover, each will have unique perspectives and work styles (Behie and Henwood, 2017; Polat and Yılmaz, 2020). The rapid development of digital technology has fundamentally transformed people's lives, creating a distinction between the generations born into the digital world, known as "digital natives," and those who adopted these technologies later in life, referred to as "digital immigrants" (Prensky, 2001; Wrobel-Lachowska et al., 2018). Digital natives have distinct characteristics, including a preference for receiving information at high speed, parallel processing, multitasking, performing better when networking, and thriving on instant gratification and frequent rewards. In contrast, digital immigrants mostly follow a slower pace; they prefer performing individual tasks rather than multitasking (Prensky, 2001). The nature of learning differs between the two groups, posing another challenge for employers to successfully manage a multi-generational workforce where older workers represent a considerable proportion.

An aging workforce represents a challenge to many industrial firms, as they must develop age-inclusive policies and practices, provide training for up-skilling, design workplaces considering ergonomics, consider health and ensure well-being, manage multi-generational dynamics, manage knowledge effectively, plan retirement, and ensure financial security (International Organization for Standardization, 2022). The Later Life Workplace Index, introduced by Wilckens et al. (2021), outlined nine organizational practice measures essential for successfully engaging an aging workforce, in which they emphasized the imperative of lifelong learning, achieved through continuous education and training.

The contribution of this study is threefold. First, it provides a comprehensive synthesis of the current knowledge on aging workforce learning in the manufacturing and service sectors. Second, it identifies what influences older workers' learning process. Third, it highlights learning approaches beneficial for older workers and proposes a socio-technical system approach to enhance and streamline learning for the aging workforce. Our findings hold significant implications and insights for researchers, practitioners, and policymakers whose interests feed into managing and supporting an aging workforce in the identified sectors.

The rest of the paper is structured as follows. Section 2 provides the research background and motivation and presents our conceptual framework for classifying, analyzing, and consolidating the gathered knowledge from the literature sample. Section 3 describes the literature search method and article selection process, followed by a descriptive analysis of the sampled articles. Sections 4 and 5 present our findings, aligning them with the conceptual framework. Section 6 outlines the proposed approach to enhance aging workers' learning from a socio-technical system perspective, and Section 7 concludes the work with several remarks and suggests future research directions.

2. Conceptual background

2.1. Aging and learning at the workplace – insights from previous reviews

The literature shows a growing interest in understanding the implications of an aging workforce in manufacturing and services (Thun et al., 2007; Calzavara et al., 2020; Di Pasquale et al., 2020; Husic et al., 2020; De Lange et al., 2021; Mok et al., 2021 Beier et al., 2022). De Lange et al. (2021) reviewed the literature for empirical studies on the relationship between different age conceptualizations and indicators of employability. They found a strong and consistent negative correlation between calendar age and the employability of workers and stressed the need to find employability measures besides calendar age. Di Pasquale et al. (2020) reviewed the literature on the relationship between human-system errors and workforce aging in manufacturing contexts, finding that experience enhances human performance and reliability, thus counteracting the decline in capabilities due to aging. Calzavara et al. (2020) reviewed the literature for studies on how functional capacity changes with age, industrial engineering models that consider the work capacity of older workers, analysis and exploitation of the expertise of older workers, and supporting technologies to assist the aging workforce. They concluded that developing learning and forgetting models considering age has received little attention and recommended investigating these models in the presence of supporting technologies.

Jeske and Roβnagel (2015) argued that understanding how learning abilities decline with age might result in designing adequate performance measures and intervention policies to enhance training and development engagement and performance. Jeske et al. (2017) identified personal and organizational resources that positively affect older workers' participation in training programs and improve their learning experience and performance.

Glock et al. (2019) reviewed a large number (457) of articles that apply learning curves in production and operations management and describe how a worker's performance improves by gaining experience while performing repetitive tasks. However, their results reported nothing on the effect of worker age on the learning curve or learning rate. Sgarbossa et al. (2020) indicated that analytical models for production systems ignore older workers' cognitive and physical limitations.

Husic et al. (2020) highlighted that policymakers must encourage older workers to engage in lifelong learning to remain competitive, work in multi-generational work groups, and opt for gradual retirement. Mok et al. (2021) supported the findings of Husic et al. (2020), who emphasized the significance of creating a supportive workplace culture. This culture, subsequently, provides older workers with opportunities for lifelong learning to achieve their career goals. Beier et al. (2022) compared learning and training between older and younger workers to identify how they differ between the two groups and concluded that age diminishes "fluid abilities" (i.e., reasoning and solving problems requires good cognitive processing speed and memory), but not "crystallized abilities" (i.e., knowledge abilities, acquired through education and life experiences). Davenport et al. (2022) showed that older workers undergoing training are usually slow learners and less motivated. Beier et al. (2022) and Davenport et al. (2022) recommended customizing instructions to older workers' abilities, experiences, goals, and attitudes to accelerate their learning during training.

Mentoring (i.e., matching a senior worker/mentor to a junior worker), apprenticeships (i.e., one-to-one training), group mentoring,

and multi-generational teams provide learning opportunities for younger generations (Ropes, 2013). Intergenerational learning is promising, but implementing it is a complex process. Its success depends on worker-related factors like motivation, the ability to work in knowledge-building environments, managerial support, and organizational openness to age diversity. Panagou et al. (2021) presented the concept of "human factor sustainability" in the I4.0 environment, considering four categories of human factors, namely behavioral sustainability (i.e., skills, rules, knowledge, and motivation), physical sustainability (i.e., ergonomics, motor resilience, and training experience), mental sustainability (i.e., mental fatigue and cognition), and psychosocial sustainability (i.e., interaction, emotion, and perception). They cautioned that while research in industrial management emphasizes optimizing human factors in an I4.0 environment, it has considered the perspective of human operators to a much lesser extent. This approach should not be ignored when addressing older worker-related problems in the workplace. Alves et al. (2022) summarized the challenges older workers operating in an I4.0 environment face, concluding that they may require work schedules and job rotations that suit their physical and cognitive abilities, skills, and experiences. They further added that the "learning factories" concept of Wolf et al. (2019) might facilitate experience-based learning for an aging workforce to help them deal with the challenges of I4.0 technologies.

In their recent review, Alves et al. (2023b) investigated how technologies, especially motion capture and virtual reality (VR) systems, can be utilized in training, learning, communication, ergonomic analysis, and workplace design for older workers. They underscored the effectiveness of immersive VR (IVR) in aiding older workers to maintain and enhance essential motor skills. This, in turn, improves their capacity to perform daily work activities and minimizes risks associated with aging, such as falls and mobility issues. The review also stressed the importance of understanding the interaction between aging workers and digital technologies. It highlighted the challenges in integrating these technologies into industrial settings with older employees and addressed the need to overcome barriers to training and acceptance of advanced tech devices.

2.2. Motivation for this review

Thun et al. (2007) showed that older workers generally have more experience, practical knowledge, work ethics, discipline, reliability, quality awareness, punctuality, social competence, and loyalty. However, they may have challenges with traits like concentration, the willingness and ability to learn, flexibility, and teamwork. While these traits are valuable in many work environments, including I4.0, older workers' adoption of the traits is inconsistent. However, individual variations exist within any age group, and not all older workers exhibit these challenges. To ensure effective workforce transformation with new technologies, it is necessary that the training and development managers fully understand how aging influences learning and promotes the factors that accelerate it.

Researchers have addressed the conversion of workers into smart workers by enhancing and supporting their work using digital technologies, also known as "Operator 4.0" (Ligarski et al., 2021; Mark et al., 2021; Dornelles et al., 2022; Ozkan-Ozen and Kazancoglu, 2022). Ashta et al. (2023) explored the concept of "Operator 5.0" in connection with Industry 5.0 (I5.0), the next generation of I4.0, with a focus on creating more human-centric, resilient, and sustainable systems (Neumann et al., 2021; Grosse et al., 2023). I5.0 represents a paradigm shift where human workers are centralized in production processes, and the technologies used to support them in the workplace (Alves et al., 2023a). The human role in monitoring and managing smart manufacturing systems of I4.0 transforms into a co-working environment with cognitive technologies with I5.0 (Hozdić and Makovec, 2023). This transformation of work includes more complex systems that require more multifaceted decision-making. Although the core principles of I5.0 emphasize humane aspects, such as human centricity and social sustainability, existing literature has not sufficiently explored the human factors (Alves et al., 2023a; Ashta et al., 2023), much less the connection between the learning needs of an aging workforce and the goals of I5.0. It is vital to address this gap, as integrating aging workers into the new paradigm is essential for leveraging their expertise and ensuring that they are not left behind in the transition.

Moreover, the learning and development of an aging workforce can contribute to achieving several Sustainable Development Goals (SDGs) (United Nations, 2015), e.g., SDG 4 (lifelong learning and quality education), SDG 8 (decent work and economic growth), SDG 10 (reduced inequalities), and SDG 12 (responsible consumption and production). Promoting lifelong learning opportunities for the aging workforce is crucial (SDG 4), enabling them to adapt to technological progress and remain active for longer. Inclusive and age-friendly work environments with advanced technologies can create productive work and economic growth (SDG 8). To address inequalities (SDG 10) at the workplace, it is important to provide older workers with equal access to learning and training opportunities, allowing them to contribute their knowledge and skills. Leveraging the expertise of older workers enhances production efficiency by reducing errors and waste, aligning with the SDG 12 aim for responsible production. Additionally, prioritizing the well-being of older workers fosters a socially sustainable environment, promoting inclusive growth and reinforcing the holistic values of responsible consumption and production.

We argue that a literature review is required to explore the relationship between the learning requirements of an aging workforce and how learning initiatives can enable them to seamlessly integrate into modern workplaces equipped with new technologies. Such knowledge would support practitioners and further research to ensure that older workers' expertise is fully utilized, rather than marginalizing them in the ongoing transition, especially in the manufacturing and service sectors. Our study aims to fill this gap and answer the following research questions:

1) What factors influence the learning of older workers?
2) Which learning approaches are most effective for this demographic?
3) How can the learning process of older workers be enhanced?

Section 4 extensively discusses the evidence from the literature sample, outlining the factors that influence the learning of older workers and providing answers to Research Question 1. Section 5 addresses Research Question 2 by discussing which literature-based learning approaches are most effective for this demographic group. In Section 6, we present an approach to enhance the learning of aging workers from a socio-technical systems perspective, offering an answer to Research Question 3.

2.3. Conceptual framework

Fig. 1 presents the conceptual framework inductively developed, following a comprehensive analysis of the selected literature sample after identifying recurring themes, patterns, and insights. This framework cohesively represents the findings and knowledge derived from these studies. We conducted a multi-level analysis that systematically explored the learning dynamics of an aging workforce. It consists of four interrelated levels that together create a comprehensive understanding of the factors influencing learning and the subsequent outcomes that result from those effective learning processes.

The foundational level analyzes the multifaceted influences shaping the learning capabilities of aging workers. We categorize these influences in Fig. 1 into three main dimensional factors: individual, organizational, and societal.

The elements of the individual category, such as physical and cognitive capabilities, attitudes and beliefs about learning and their perceived relevance, and learning applicability are called their innate

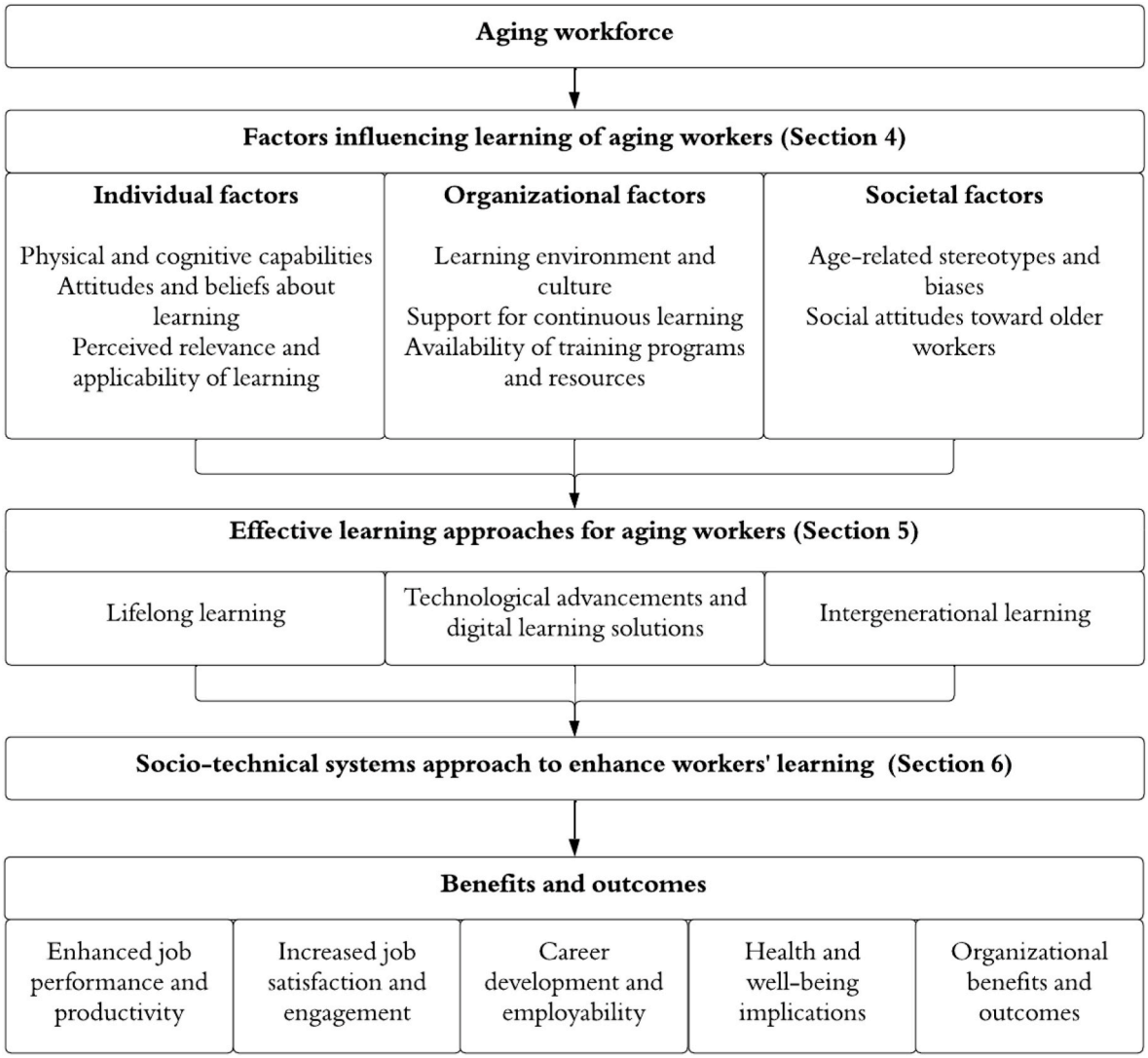

Fig. 1. Conceptual framework prepared to guide analysis.

and acquired abilities. Physical capabilities encompass an individual's stamina, manual dexterity, and motor skills, which are fundamental in tasks requiring endurance, precision, or physical coordination. Cognitive capabilities relate to an individual's mental processes. This includes their ability to memorize, reason, solve problems, and make decisions. Attitudes and beliefs about learning delve into an individual's mindset toward acquiring new knowledge or skills. Attitudes can vary from enthusiasm and curiosity to apprehension or resistance. The beliefs about learning encompass the individual's convictions about their capacity to learn—known as self-efficacy (Guerrazzi, 2014; Hall et al., 2022)— and their views on the intrinsic value of learning. For instance, some older workers might believe that learning is an ongoing lifelong process, whereas others believe it is more suited to the early stages of life or specific situations. Perceived relevance and applicability of learning gauges how an individual perceives the importance and applicability of what they are learning. If an individual sees the learning content as directly beneficial to their current role or future aspirations, they are more likely to be engaged and motivated. The more relevant the material, the higher the likelihood of its application in real-life work scenarios. Conversely, if they deem the content as disconnected from their work contexts, the learning might not be as effective or impactful. Understanding these elements is crucial as they play a foundational role in shaping an individual's learning journey, especially in the context of an aging workforce.

Under the organizational factors, we identified elements such as learning environment and culture, support for continuous learning, and the availability of training programs and resources. A conducive learning environment fosters open communication, encourages individuals to ask questions, and facilitates hands-on learning despite the workers' age. The culture reflects the organization's attitude towards continuous learning, especially focusing on older workers. Support for continuous learning ensures that workers remain up-to-date with the latest trends, tools, and methodologies in their respective fields, via mechanisms in place to encourage them to attend internal or external learning activities. Such organizations might also have policies allowing workers to dedicate a portion of their work hours to learning new skills, thereby ensuring that the workforce remains versatile and ready to address emerging challenges regardless of age. The provision of relevant training programs and resources is a tangible measure of an organization's commitment to its workers' growth. These programs, ranging from formal courses to informal mentoring sessions, should be designed toaddress the diverse learning needs of the aging workforce. These elements can support the transformation of an organization's aging workforce into a competitive, motivated, and productive one.

Age-related stereotypes and biases, as well as social attitudes toward older workers, were identified as societal elements. Age-related stereotypes often involve assumptions about an individual based solely on their age. Common stereotypes include beliefs that older workers are

reluctant to adapt to new technology, resistant to changes, and are less energetic or productive than their younger counterparts. Such biases, though frequently unsubstantiated, can create a toxic work environment for older workers and lower their self-efficacy and self-confidence. Furthermore, social attitudes towards older workers often swing between two extremes. There is the perception that they bring a wealth of experience, wisdom, and stability to the workplace specifically in higher positions of an organization. They are seen as reliable, and dedicated, and possess a strong work ethic cultivated over years of service. However, a prevailing notion can be that older workers, such as blue-collar workers at the front end of a production facility, are more expensive due to higher salaries and health benefits. Additionally, older workers are sometimes considered "blocking" positions that could be occupied by younger professionals, which further exacerbates the generational divide (Zemke et al., 2013). These societal attitudes, if unchecked, can lead to a range of negative outcomes, from reduced job opportunities for older professionals to a lack of intergenerational collaboration in the workplace.

These elements have been chosen to provide a comprehensive perspective on each factor category, reflecting the breadth and depth identified by our literature sample. These categories and their respective elements are extensively discussed in Section 4 of this paper. The second level identifies optimal learning strategies tailored to the specific needs of aging workers. In the third level, we synthesize the insights from the first two levels to develop a socio-technical system approach, drawing implications from this literature review.

This approach seeks to align social and technical aspects within organizational systems while considering elements related to the workers, the organization, and the society that affect the learning process, making the approach holistic. The fourth level outlines the anticipated benefits and outcomes of implementing the first, second, and third levels described in Fig. 1. It foresees improvements in key areas, such as job performance and productivity, increased job satisfaction and engagement, career development and employability, and health and well-being implications. These benefits translate into broader organizational benefits and outcomes.

3. Methodology

3.1. Literature search and selection process

To review the literature, we employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach (Page et al., 2021), a benchmark approach extensively adopted in research (Pilipiec et al., 2021; Alves et al., 2022). We followed three steps: (1) identify the relevant keywords and search queries, (2) search scholarly databases and cross-referencing, and (3) select relevant articles as described in Fig. 2. We created four groups of keywords (see Table 1) based on core concepts from previous literature review articles on the aging workforce in the manufacturing and service sectors and human learning. Keywords related to aging (Group 1), workers (Group 2), and industry (Group 4) are from Calzavara et al. (2020) and Di Pasquale et al. (2020), while learning-related keywords (Group 3) are from Glock

Table 1
Keywords used for searching in Scopus and Web of Science.

Group 1 -Aging	Group 2 - Worker	Group 3 - Learning	Group 4 - Industry
Aging	worker*	Learning	manufact*
Ageing	workforce	learning curve	industr*
older	employee*	learning function	production
senior*	operator*	learning effect*	assembly
elder*	labour*	experience curve	process
tenure	labor*	startup curve	service*
		forgetting curve	
		forgetting function	
		memory loss function	
		relearning function	
		re-learning function	
		progress function	
		startup function	
		startup management	

Note: The asterisk (*) represents any character or combination of characters that can appear in a word.
E.g., old* represents older, industr* represents industry, industries, or industrial.

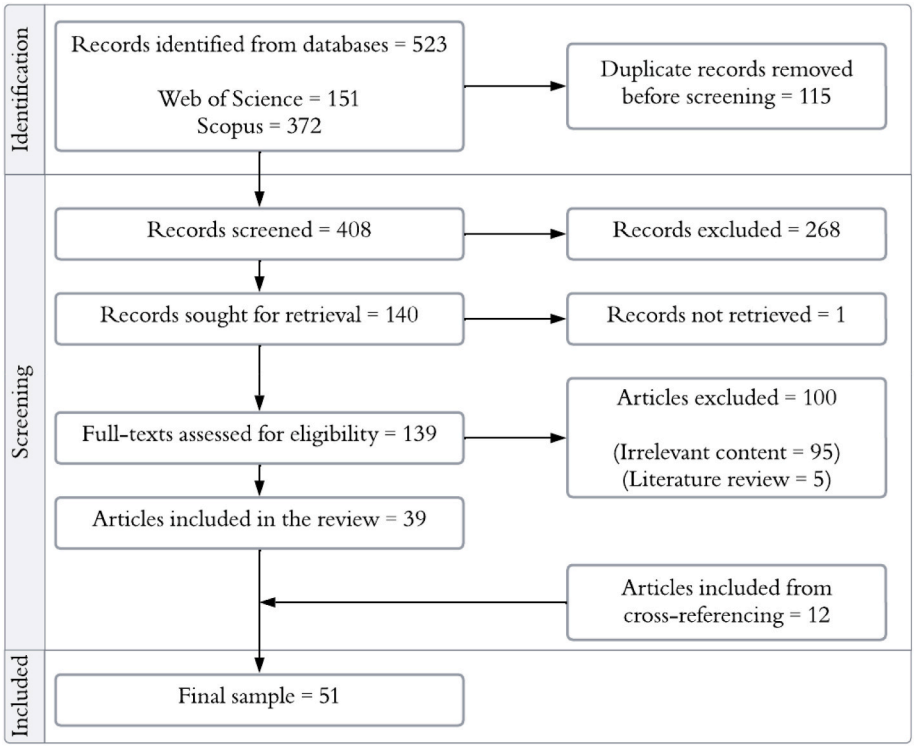

Fig. 2. PRISMA flow diagram.

et al. (2019). Then, we iteratively refined the keyword list according to the research objective.

In the identification step shown in Fig. 2, we used "OR" and "AND" Boolean operators in our keyword search. Keywords within each group were combined using the OR operator and the four groups were combined using the AND operator. In the identification step, when screening titles, abstracts, and keywords we identified some keywords (e.g., "machine learning," "deep learning," "nursing," "school" etc.) which frequently led to irrelevant articles, mainly from medical, nursing, elderly care, banking or general education fields. To refine our search and exclude these unrelated articles, we introduced the 'NOT' Boolean operator in our final keyword string. The complete search query, as implemented in Web of Science, is detailed in Appendix A. This strategy was preferred over database-specific field selections to ensure we did not inadvertently narrow our scope, thus maintaining a multidisciplinary perspective essential for exploring learning in the context of an aging workforce. We searched the Scopus and Web of Science databases which are comprehensive databases often used for systematic literature reviews in management research (Sauer and Seuring, 2023) and cover multidisciplinary research. We searched for titles, abstracts, and keywords of articles published in both journals and conference proceedings on or before November 15, 2023, in English. Additionally, we consulted with a librarian at one of the co-authors' institutions to ensure the robustness of our search strategy. The librarian double-checked the keywords and database syntax used and confirmed our methodological approach to be suitable.

As shown in Fig. 2, we obtained 408 records for the screening step after removing 115 duplicates. Subsequently, we screened titles, abstracts, and keywords and excluded articles that did not meet the following criteria.

1. Content: studies analyzing, discussing, and focusing on the learning of aging workers in manufacturing or service (transportation and utilities) industries.
2. Publication type: conceptual or empirical study (not literature reviews).

One hundred and forty records were selected to retrieve for full-text screening and using the same exclusion criteria, we identified 39 articles relevant to our scope. Furthermore, cross-referencing resulted in another 12 articles, which made a final sample of 51 articles.

A classification of the literature sample based on the conceptual framework is provided in Table A2 (Appendix).

3.2. Descriptive results

We have analyzed the literature sample descriptively in terms of (a) publication year, (b) countries in which the research in those articles was conducted, (c) research methods used, and (d) keywords co-occurrence networks. Fig. 3 illustrates the distribution of published articles over time, showing that worker aging has been a research topic for over four decades since the aging predictions came to light (Ilmarinen, 2001). The highest number of published articles in a single year was in 2015, with 61% of the sample articles published after 2014, reflecting the increased interest following this year. This may be due to emerging challenges faced by employers and employees raised by contemporary issues due to the aging workforce (see Section 2). Fig. 4 depicts the geographical distribution of the countries where the studies included in our sample were conducted. This represents the locations of the samples/subjects used for the research, as stated in the respective papers, rather than the authors' affiliations. Importantly, this distribution aligns with the observation that countries with significant aging populations have extensively researched the challenges and opportunities associated with an aging workforce, as noted by the UN in 2022 (United Nations, 2022).

Fig. 5 illustrates the research methods used in the literature sample.

Table 2
Strategic parameters for aging workforce development.

Parameter	Older workers	Organization
Mindset	Openness to learn and develop. Willingness to share knowledge. Adapting to changing technological landscapes.	Valuing the experience and wisdom of older workers. Inclusivity toward aging workforce. Commitment to provide lifelong learning.
Skillset	Accumulated experience and expertise. Ability to mentor younger peers. Tacit knowledge.	Providing training tailored to age groups. Training to develop skills for intergenerational collaboration. Training to develop management skills for age-diverse teams.
Toolset	Familiarity with older tools, processes, and technologies.	Age-inclusive workplace and work design. Providing age-inclusive technological infrastructure. Designing user-friendly digital platforms. Offering diverse learning methods.
Dataset	Personal experience of past projects, outcomes, and lessons learned. Individual's collection of knowledge from past training and education.	Aggregate data on workforce demographics. Data on learning program outcomes. Data analytics and interpretation capabilities. Insights on the effectiveness of technological tools for different age groups. Knowledge management systems.

Of the articles, 16 utilized qualitative research methods, primarily through individual and/or group interviews or surveys (e.g., questionnaires); 10 reported findings from experiments conducted on the aging workforce, examining their cognition and task performance in various settings and industries, using a quantitative approach; and 9 employed mixed research techniques, combining both quantitative and qualitative methods. Only eight articles fall under the "other" category, presenting conceptual, viewpoint, or theoretical content.

Fig. 6 shows the co-occurrence network visualization diagram of the sample keywords created using VOSviewer Software (Van Eck and Waltman, 2010). It shows the keywords that co-occurred in the literature sample and the clusters to which they belong. The network diagram has 35 nodes that fall into four clusters, differentiated by color (blue, green, yellow, and red). These clusters informed the conceptual framework discussed in Section 2.3, contributing to a comprehensive understanding of learning processes among aging workers. Cognitive and psychological factors influencing learning in older adults are represented in yellow and red respectively, highlighting age-related changes and individual differences. The green cluster focuses on age management, technology, and training strategies suited to older workers' needs, emphasizing age-related factors in fostering effective learning environments. The blue cluster investigates knowledge management, retention, and transfer for older workers phasing out.

4. Factors influencing learning among aging workers

We identified factors influencing the learning of aging workers; they fall into three categories: individual, organizational, and societal.

4.1. Individual factors

Individual factors are divided into three sub-categories: (1) physical and cognitive capabilities, (2) attitudes and beliefs about learning and perceived relevance, and (3) applicability of learning. A worker's physical and cognitive abilities diminish with age, slowing that worker's learning. Factors such as impaired vision or hearing, lower cognitive flexibility, or decreased dexterity usually require accommodating older

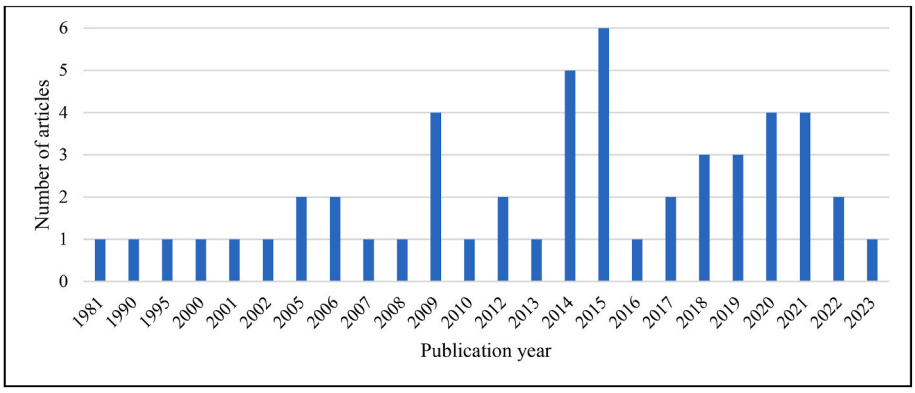

Fig. 3. Publication year distribution of the literature sample.

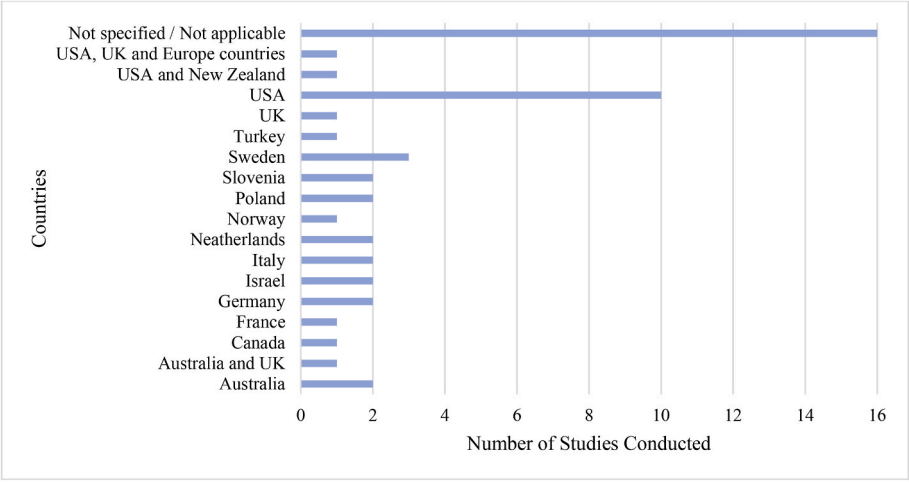

Fig. 4. Geographical distribution of the locations of the samples used in the analyzed papers.

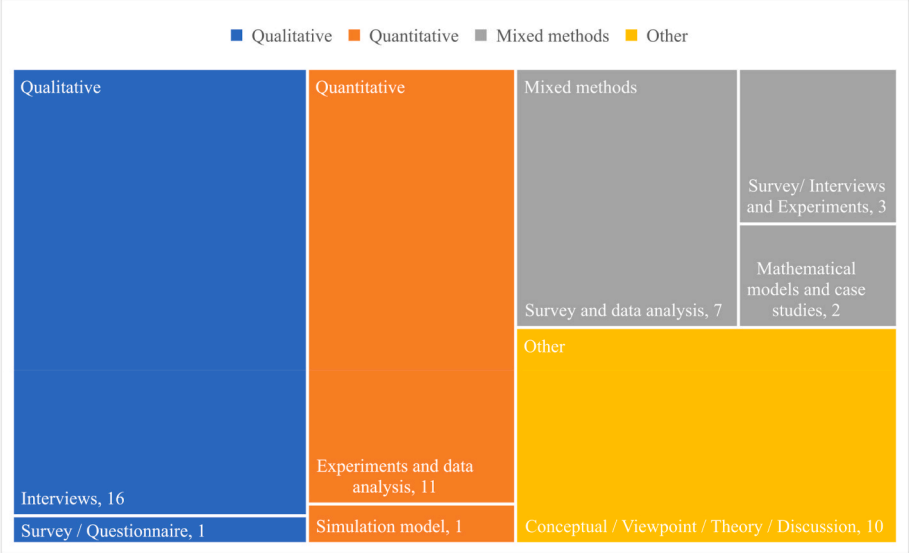

Fig. 5. Research methods used in the literature sample.

workers or adjusting their learning methods.

In our sample, Czaja and Drury (1981) empirically studied the learning of aging workers performing industrial inspection tasks. They observed that the inspection speed and number of errors were higher for older workers. They also concluded that active learning (instructions with practice) rather than passive learning (instructions without practice) improves older workers' learning and employability. Einstein and McDaniel (1990) studied the impact of age on prospective memory

Fig. 6. Co-occurrence network visualization diagram of keywords in the literature sample.

(remembering information to recall in the future) and retrospective memory (remembering events/experiences of the past). Older and younger workers' performance was similar on prospective memory tests, with the younger ones outperforming older workers on retrospective memory tests. Einstein and McDaniel (1990) concluded that aging puts retrospective memory at risk; thus, companies need strategic actions to preserve the accumulated knowledge of older workers.

Digiesi et al. (2020) proposed a model to estimate information processing time to assess individuals' motor and cognitive abilities across different age groups. They applied the model to an automotive assembly line to examine the impact of aging on job processing time in workstations by varying automation levels to alter the cognitive and motor content of the task. Their results showed that processing time increased with age workers performing either task types (cognitive or motor), and this must be considered when assigning older workers to workstations, especially in digital work environments. Abubakar and Wang (2019) studied how age affects learning, showing that performance peaks for workers at 38 years of age and starts deteriorating beyond that age, arguing that accumulated experience may compensate for this deterioration. In another study, Abubakar and Wang (2018) described a method for evaluating worker performance by incorporating age and experience as a learning curve into a comprehensive Discrete Event Simulation (DES) model. They observed that existing simulation tools lack functionality, particularly in accurately reflecting workers' learning curves, age, and experience. The study emphasized the need for more sophisticated, integrated, and cost-effective DES solutions.

Notably, many older workers possess valuable accumulated experience that can act as a buffer, compensating for some of these cognitive declines. Ilmarinen (2001) found that age impedes cognitive processes but not performance, as the experience of older workers usually compensates for that. Nunes and Kramer (2009) corroborated Ilmarinen's (2001) finding and concluded that the ability to work, and not age, should be the factor for keeping workers in their jobs. Hall et al. (2022) experimented with two groups of operators, novice and experienced. They observed a significant correlation between increasing age-reduced accuracy and slower reaction times in the novice group. However, among expert operators who were between 44 and 61 years of age, this trend was not as apparent, suggesting that their experience may attenuate age-related declines in performance.

Volkoff and Pueyo (2005) discovered that with experience older workers increasingly learn and develop strategies to manage time pressure at the workplace. However, they emphasized that mitigating unnecessary time pressure is crucial for the health and productivity of the aging workforce from an ergonomic perspective. Therefore, Volkoff and Pueyo (2005) highlighted that work organization models which are often rigid and unadaptable must be reassessed in this context, particularly regarding time constraints, to benefit not only older workers but all workers.

There is also research on the cognition and learning of an aging workforce post-retirement. For instance, De Grip et al. (2015) empirically tested the relationship between retirement and cognitive development for older workers by evaluating their memory, cognitive flexibility, and information-processing speeds. Their results indicated that retirees faced less decline in cognitive flexibility compared to those who remained employed. This effect remained persistent even after being retired for at least six years. Conversely, the study found a more significant decline in information processing speed among retirees, particularly those with lower levels of education. They suggested that the increase in cognitive flexibility among retirees could be due to their involvement in a broader range of activities, such as volunteer work, travel, and other intellectually and socially engaging tasks. De Grip et al. (2015). emphasized the complex relationship between retirement and cognitive development, indicating both positive and negative cognitive implications of retirement, and underscored the need for policies that consider these diverse cognitive outcomes.

Furthermore, older workers' attitudes are pivotal in their ability to adapt and learn. Maintaining a positive and proactive attitude toward learning is essential for workers to remain relevant in their respective fields. Hall and Mirvis (1995) emphasized the importance of meta-skills (i.e., learning how to learn) with the shift from traditional linear careers to more self-directed, protean career paths. They identified two key meta-skills: (1) identity development which involves ongoing self-reflection and adaptation of one's professional identity, and (2) adaptability, which is the ability to adjust behaviors and attitudes to meet evolving work demands and embrace a career characterized by rapid changes, diverse roles, and continuous learning.

Roβnagel et al. (2009) noted that self-regulated learning requires learning competency on three levels: (1) cognitive (using learning strategies to connect new knowledge to previous knowledge), (2) meta-cognitive (self-planning, self-regulation, and self-evaluation of learning through specific goals), and (3) motivational (aiming for a learning or performance goal). Equally important is the perceived value or relevance associated with the learning process. This perception can motivate older workers to engage more deeply and effectively in learning. Žnidaršič et al. (2021) demonstrated that older and younger workers were equally motivated to learn and undergo training, albeit driven by distinct motives. Older workers focused on improving work efficiency and productivity, while younger workers focused on fulfilling career goals. Grah et al. (2019) presented a case study of a high-end fashion designer who remained competitive after reaching the official retirement age. They also highlighted the strategies to deal with this. Those strategies include positive emotions, vitality, intrinsic motivation, and adapting to lifelong learning.

We categorized individual factors affecting the learning of older workers into three sub-categories: physical and cognitive capabilities, attitudes and beliefs about learning, and applicability of learning.

Studies in this category reveal that, although older workers typically exhibit slower learning rates, differing memory capabilities, and longer processing times compared to their younger counterparts, their rich accumulated experience often offsets these challenges. Crucially, tailoring workplace tasks and learning methods to align with the abilities and experiences of older workers is vital; such adaptations are key interventions that significantly enhance their learning effectiveness. Furthermore, the analyzed studies highlight the importance of attitudes and adaptability in older workers. Positive mindsets and proficient self-regulated learning competencies emerge as crucial factors for their continued effectiveness and success in rapidly evolving work environments.

4.2. Organizational and societal factors

In this paper, we explore the interaction of aging with organizational and societal factors affecting how workers learn. Organizational factors include aspects such as the learning environment and culture, the support for continuous learning, and the availability of training programs and resources. Societal factors encompass age-related stereotypes and biases, including societal attitudes toward older workers.

Hall and Mirvis (1995) emphasized the need for organizations to recognize individual differences in older workers' motivations and abilities which then lead to individualized learning strategies. They proposed four innovative sources of learning: (1) building relationships, (2) gaining varied experiences to enhance adaptability, (3) better brokering of assignments and roles to facilitate development, and (4) utilizing information technology for various functions such as recruiting, staffing, self-assessment, career services, and enhancing group or organizational learning.

Güttel et al. (2009) proposed four functional configuration types based on the internal learning dynamics of an organization. First, exploration configuration, in which highly evolving markets drive the industry to update worker competencies. Second, the exploitation configuration is driven by irregular worker competency and moderately dynamic markets. Third, blending exploration and exploitation, known as ambidextrous organizations, in which regular work routines and product or process innovations are equally weighted and guided by a logical approach. Fourth, dysfunctional configuration, where market expectations do not match workers' competencies. The expertise and skills of workers form the foundation for achieving and maintaining an organization's competitive edge. Güttel et al. (2009) recommended creating internal learning dynamics and strategies to overcome the old age barrier to avoid impeding continuous improvement and updating employees' competencies. Guerrazzi (2014) investigated the relationship between training propensity and aging in manufacturing firms of various sizes and showed that large firms are more likely to offer training than small firms. There was also an inverted U-shaped pattern in companies' willingness to train their workers, and they were more willing to provide training to middle-aged workers than to younger and older workers.

Smith et al. (2010) conducted an interview-based study of employers to find that they considered older workers assets rather than liabilities, as they, compared to young workers, were reliable, recognized the imperative for change, and engaged more actively in it. However, their study reported that older workers had apprehensions regarding training and learning new technologies, as they faced negative attitudes, including ageism and stereotypes. Smith et al. (2010) emphasized the importance of customized training designed to meet the needs of older workers as a countermeasure. Kadefors and Hanse (2012) found that not having up-to-date competencies and negative attitudes toward and by older workers are significant barriers to their continued employment and employability. Notably, attitudes toward older workers varied based on the sex of both the employer and older workers. Ng and Law (2014) cautioned that negative attitudes toward older workers lower their worth in the labor market. They recommended employers provide older workers with emotional and physical support by avoiding internal stereotypes and discrimination and to gain from their experience and enhance it through investing in training, work redesign, and flexible work arrangements.

Migliore (2015) interviewed older workers who worked on a mass-production assembly line and a flexible production system to explore their engagement in work and learning. Older workers were more motivated to work and learn in a flexible production system because of the opportunity to learn new techniques, their passion for work, and the professional knowledge they gained. In the mass assembly facility, older workers focused on maintaining quality while adhering to organizational and safety rules, thus slowing their performance. Nonetheless, they valued their work and thrived on improving and learning more. Migliore (2015) recommended employers consider previous learning experiences of older workers, financial incentives, subjective relationship with their jobs, and cultural and historical background when formulating work and learning policies to promote innovative work environments.

Verworn et al. (2009) argued that proactive training of all age cohorts is more effective than reactive training. Developing skills, knowledge, and attitudes helps prevent or manage the consequences of problems, suggesting that proactive training better serves firms than reactive training. They also noted that hands-on learning techniques are more effective in facilitating the learning of older workers.

Beck (2014) examined the views of employers in the UK regarding older workers, noting significant differences in the value placed on those workers' knowledge and experience across different sectors and occupations, where some sectors highly valued their expertise (e.g., senior management), while others saw them as a disadvantage (e.g., assembly line operations). They also emphasized that a more equitable approach to valuing individual skills, knowledge, and experience would make a workforce more productive. Findsen (2015) highlighted the need to challenge stereotypes and myths surrounding older adults' learning capabilities and address ageism in the workplace. They stressed that older workers should have equal access to training and development opportunities where managers are responsible for creating an inclusive work environment for older workers. Pfrombeck et al. (2023) added that creating an environment where older workers appreciate and value intergenerational interactions is essential. When older workers have positive feelings towards working and interacting with younger peers, it can mitigate negative feelings, such as embarrassment, that might otherwise hinder knowledge exchange.

Delgoulet and Marquie (2002) studied the effects of age and experience on learning anxiety, strategies, and performance in a group of workers of different ages participating in a one-week maintenance training course. Their results showed that although older trainees' prior experience did not make them less anxious, it did not affect their performance. They found that the performance of older and younger trainees was comparable after several trials, suggesting older workers undergo more frequent training. Wiker et al. (2006) and Schwerha et al. (2007) investigated how age affects learning an assembly task in an environment with visual and auditory distractions similar to what workers face in a production environment. They recorded the assembly time and errors for four distraction scenarios: no distraction, auditory distraction, visual distraction, and both auditory and visual distractions. The results showed that older workers demonstrated slower learning rates and made more errors when performing a new psychomotor task than their younger colleagues for all distraction types. Older workers also needed much more repetitions to learn, almost twice the average when distractions were auditory and visual, recommending environments with fewer distractions.

Verneau et al. (2014a) studied the impact of aging on both explicit (conscious learning through effort and movements) and implicit (unintentional learning without deliberate knowledge acquisition about the movement) motor learning in assembly workers. Their results confirmed that explicit learning declines with age, while implicit does not. They

suggested slowly delivering instructions explicitly to older workers at a slower pace for effective learning. Verneau et al. (2014b) showed that the performance of younger workers was not affected by the type of instruction, whereas older workers were better with full instructions than guided learning. This method enhanced their memory and knowledge consolidation of the assembly task structure and dynamics, and Verneau et al. (2014b) suggested that workers' age should be considered when providing instructions.

To sum up, the multifaceted interaction between older workers and organizational and societal factors significantly influences their learning dynamics. The organizational landscape plays a crucial role, with elements such as continuous learning support, the nature of the learning environment, and tailored training programs being instrumental. Societal challenges, particularly age-related biases and stereotypes can impede the learning and integration of older workers and require proactive measures to address them. Our literature sample suggests that while older workers bring a wealth of experience and expertise, acknowledging their distinct learning needs and barriers remains paramount. Addressing these unique needs, ranging from adjusting the pace of delivering instructions to considering hands-on learning techniques, can optimize the learning outcomes for older workers. Moreover, internal organizational dynamics, training proclivities, intergenerational interactions, and attitudes of both workers and employers significantly mold the learning experiences of this demographic.

5. Effective learning approaches for aging workers

5.1. Lifelong learning

Our sample focuses on lifelong learning of the aging workforce in the manufacturing and service sectors and their impact on retirement and post-retirement careers.

Findsen (2015) discussed formal, informal, and non-formal learning opportunities for older workers in changing workplace environments. Formal learning follows structured and intentional educational activities through educational institutions, employers, training programs, or workshops. Informal (or incidental) learning occurs through trial and error and on-the-job learning (i.e., learning by doing), for example, through observing, trying, and learning from more experienced workers. Non-formal learning methods are between formal and informal. It is systematic and organized, occurring in a non-educational setting. Findsen (2015) stressed that utilizing these learning methods helps retain productivity in an ever-changing workplace environment.

De Grip (2015) reported that up to 96% of the time workers spend on learning was on-the-job and that informal learning approaches vary by country/culture and firm's atmosphere, adding that the productivity of older workers is higher in industries with rapid rather than slow technological changes. Roβnagel et al. (2009) revealed that older workers performed worse than younger workers on learning competency measures (e.g., memory span) and that a positive learning climate and continuous learning opportunities help reduce the negative effects of aging on learning performance.

Ravichandran et al. (2015) recommended eliminating age bias, focusing on workers' knowledge, skills, and capabilities, and implementing training programs to encourage lifelong learning. Their study also suggested using technology-friendly tools with real-time feedback as an independent and self-paced learning method for older workers. Face-to-face discussions are also recommended to address any potential intimidation related to using new technology. Further, although older workers prefer on-the-job training, managers should break down training components into smaller, more manageable units and be flexible in accommodating the diverse learning styles and experiences of older workers.

According to Bercovici and Bercovici (2019), I4.0 technologies present challenges and opportunities for all stakeholders (employees, employers, and employment agencies). Interestingly, there was almost a consensus among the interviewees to extend the retirement age to 70–75 years. The authors also emphasized that to remain competitive, employees need to be proactive in their job mobility and learn new skills, while employers need to allocate necessary resources to support employees of all ages to adapt to working with older employees and provide them with the services they need.

5.1.1. Lifelong learning, retirement, and post-retirement

In a longitudinal, qualitative study, Furunes et al. (2015) followed a sample of older workers over three years to capture their reflections on late careers, retirement planning, and decision-making. They found that older workers value demanding work with varied tasks that allow them to learn new skills and that workers with such challenging and dynamic jobs tend to delay retirement.

Unson and Richardson (2013) discussed an "encore career," a career pursued at the end of mid-life to continue beyond the traditional retirement age. They found that being open-minded to change and seeking support helped manage the changes in older workers' careers. Eppler-Hattab (2021) investigated the concept of lifelong learning and its implications for entrepreneurial self-employment later in life (i.e., post-retirement) and suggested that such active learners can have lifelong employability and benefit from their accumulated knowledge and life experiences in productive and empowering ways as entrepreneurs.

5.2. Technological advancements and digital learning solutions

Becker et al. (2012) gathered and analyzed information from learning and development practitioners and stakeholders on using e-learning in various rail organizations. They found barriers to adopting and using e-learning across workers of all age groups and with different levels of technological literacy since not all digital natives were technology savvy and not all digital immigrants were technologically illiterate. Wrobel-Lachowska et al. (2018) addressed the integration of Logistics 4.0 (see Winkelhaus and Grosse, 2020), emphasizing the urgent need for upskilling older workers in digital competencies for system operation and management. The rise of e-commerce and the Internet of Things (IoT) devices and systems in warehouse operations and inventory management, necessitates workers to utilize information and communication technology (ICT) tools, particularly in blue-collar jobs. Wrobel-Lachowska et al. (2018) recommended implementing a knowledge management system to bridge the digital skill gap. A core strategy of this system is to pair technologically adept workers with their less experienced counterparts, complemented by the development of user-friendly ICT tools equipped with straightforward instructions.

Beinicke and Kyndt (2020) investigated how a successful learning process affects training effectiveness in transferring what is learned to the workplace. They showed that companies generally implement transfer-supportive actions before and during training in e-learning and classroom settings. However, there was room for improvement, particularly in meeting the needs of older workers, integrating error management, and evaluating training at multiple levels.

Researchers have discussed the utilization of I4.0 technologies, such as VR and augmented reality (AR), to enhance workers' training in general (Calzavara et al., 2020; Dornelles et al., 2022). Forest (2021) discussed how petroleum refining and petrochemical industries face the challenge of transferring years of knowledge from older workers to the younger generation, mainly due to differences in learning styles and fewer opportunities for hands-on learning. They stressed the role state-of-the-art technologies (e.g., VR) play in mitigating these training challenges and improving learning experiences for all ages. Dobrowolski et al. (2021) discussed the impact of age on the efficacy of IVR-based training methods over non-interactive (i.e., text and video) training in learning a new skill, showing that the performance of younger and older workers was similar and improved with the IVR method, especially for older workers.

5.3. Intergenerational learning

Salopek (2000) emphasized the need to tailor training methods to workers' learning styles, which vary with age. They noted that while younger workers prefer fast-paced learning, older workers value learning at their own pace and appreciate recognition of their experience. Salopek also highlighted that training can be stimulating and enlightening for all ages when an appreciation for participation and motivation to learn exists. Similarly, Behie & Henwood (2017) underscored the importance of adaptable training and development programs in multi-generational workplaces. They advocated for accelerated learning solutions that contrast with traditional methods used for older generations, such as boomers and early Gen X. They emphasized the benefits of blended learning, which combines practical experiences with other teaching methods, and the necessity of customizing training programs to meet the evolving needs of the workforce.

Brooke and Taylor (2005) analyzed how introducing new technologies in two organizations in two countries resulted in tensions between older and younger workers when seniority was ignored. Consequently, the career trajectories of older workers either plateaued or declined with the loss of skills and experience and disunity between the two age groups. Brooke and Taylor (2005) argued that management and policymakers should pay close attention to workforce diversity and reform employment practices to avoid hostile work environments. They emphasized that individual attributes and capacities should be prioritized over age-based assumptions in training and promotion decisions.

Gellert and Kuipers (2008) explored the impact of workers' age on work teams to find that those with a higher average age resulted in better job satisfaction, peer learning, feedback, decision-making, product quality, fewer sick and burnout leaves, and preferred a balanced production schedule. This showed that an aging workforce can positively affect work teams' development and performance. For instance, Kadefors and Hanse (2012) reported that many employers use mentorship learning programs to share the competence and experience of older workers with younger ones through daily communication and cooperation activities. Evans (2017) recommended that organizations focus on understanding the differences in skills between digital natives and immigrants and encourage both groups to learn from each other through mentorship programs. Wikstrom et al. (2018) explained that "knowledge" and "knowing" are two different concepts, and retention of tacit knowledge is an iterative process of daily interactions and collaborative events.

Gerpott et al. (2016) described how intergenerational learning facilitates the transfer, sharing, and creation of knowledge and restructuring among young and older workers and supports preserving organization-specific knowledge and expertise within the workforce. They also proposed a classification framework for intergenerational learning based on the degree of formality (i.e., formal or informal) and the direction of knowledge exchange (i.e., unidirectional or bidirectional). Formal learning activities are structured and informal learning activities are unstructured. Unidirectional learning occurs when younger workers learn from older workers, whereas bidirectional learning occurs when both workers learn from each other. Accordingly, learning of younger workers from older workers is informal and unidirectional, whereas when older workers learn from younger workers, it transforms into an informal bidirectional learning community. Mentoring programs can be categorized under formal unidirectional learning activities, while structured training programs and seminars can be utilized as formal bidirectional learning avenues. Gerpott et al. (2016) also highlighted participants' intentions to share knowledge, stereotypes, or attitudes toward other generations, anticipated benefits or threats, and knowledge self-efficacy (i.e., confidence in one's knowledge and competencies) as factors that affect intergenerational learning success. They further noted that success in activity-based learning also hinges on factors like the willingness of participants to volunteer, the duration of the learning activity, support from professional institutes, task complexity, and goal clarity.

Polat and Yılmaz (2020) explored specific barriers to effective intergenerational learning and categorized them into three groups: personal, relational, and managerial. Personal factors include viewing knowledge as power, lack of job commitment, resistance to change, differences in generational expectations, and avoiding personal development. In the relational category, significant barriers include communication problems, generation gap conflicts, lack of respect and empathy between generations, and inadequate role models. Managerial barriers identified include a lack of management support for intergenerational learning, heavy workloads, unsatisfactory job designs, unfairness, and lack of intergenerational teamwork. Wrobel-Lachowska et al. (2018) proposed a knowledge management system must be designed to address the digital skill gap between different generations in the workforce which encourages the sharing of knowledge and skills across generations. Furthermore, knowledge management systems and intergenerational learning are not limited to tacit knowledge or skills transfer; it is also about the exchange of ideas, perspectives, and work ethics. This interaction helps in building a more inclusive, understanding, and cohesive workplace culture.

Ashworth (2006) cautioned that the retirement of older workers comes at the cost of knowledge loss, knowledge transfer between retirees and newcomers, and the replacement of retiring leadership. To minimize the cost to a firm, Ashworth (2006) emphasized the need to coordinate and facilitate knowledge transfers between retirees and new workers well in advance and recommended establishing "transactive memory networks" for sharing and coordinating knowledge to ensure that vital knowledge is retained within the firm and performance is sustained or improved. Cox and Overbey (2022) advocated developing a succession plan to monitor the internal knowledge transition and utilize the time via phased retirement plans. They also suggested job shadowing sessions where older workers review the work of younger workers and share their experiential knowledge and best practices, allowing both to interact with each other and younger workers to learn by doing and gain hands-on experience. Moreover, Cox & Overbey (2022) suggested re-employing older workers post-retirement as mentors or trainers to avoid knowledge depreciation and strengthen knowledge transfer. Guvernator and Ernesto (2020) investigated how informal knowledge transfer occurred in the utility industry and referred to the five knowledge transfer methods of Dixon (2000): (1) serial transfer (a group of workers using the knowledge gained while doing a task for a different task in a different context), (2) near transfer (knowledge sharing between groups doing similar tasks in similar locations but different contexts), (3) far transfer (tacit knowledge transfer between groups about a non-routine task), (4) strategic transfer (knowledge transfer between teams separated by time and space; implementing this knowledge affects the system significantly), and (5) expert transfer (transferring expert knowledge, not necessarily on a frequent task), based on the nature of the knowledge receiver, frequency and nature of the task, and the type of knowledge shared. Guvernator and Ernesto (2020) suggested that understanding the need for knowledge transfer in each context (e.g., repairs of machines, introducing new products or processes, or standard operating procedures) and mapping the methods used can bring the needed improvements or revisions and ensure that knowledge transfer is consistent among workers.

Pfrombeck et al. (2023) recently investigated how knowledge-seeking from younger coworkers by older workers affects their work experience as they age. Pfrombeck et al. (2023) discovered a positive link between older workers learning from younger colleagues and their increased motivation and workability, primarily driven by perceived learning. However, they also noted a negative impact on workability associated with the embarrassment older workers might feel in such interactions.

To sum up, effective learning approaches for aging workers encompass a balance between acknowledging cognitive and physical challenges and leveraging their rich experience. A combination of formal,

informal, and non-formal learning opportunities plays a crucial role in maintaining productivity. Proactive training and fostering positive work environments are essential, not only for effective learning but also in combating age-related stereotypes. Research across age groups identifies barriers to e-learning adoption, suggesting that this is a widespread issue and not confined to older workers alone. However, the advent of Industry 4.0 technologies, such as VR and AR, offers new opportunities to enhance training effectiveness across generations (Neumann et al., 2021). Additionally, intergenerational learning emerges as a critical component in the transfer of knowledge within the workforce. The success of this learning depends on a blend of formal and informal methods and is influenced by factors like stereotypes, participants' willingness, and the complexity of the task at hand. These elements, when effectively managed, can facilitate a productive and inclusive learning environment for all age groups in the workforce.

6. Socio-technical system approach to enhance learning for the aging workforce: A proposition based on the review

6.1. Strategic parameters for aging workforce development

In our systematic literature review, we discussed the individual, organizational, and societal factors that influence the learning of aging workers and effective learning approaches for them. Subsequently, the following question arises: How can this knowledge be put into action? As we strategize the transition of an aging workforce to modern workplaces equipped with cutting-edge technologies, a structured approach is paramount. We considered all parameters of the *mindset, skillset, toolset, and dataset* framework proposed by Fleisher (2021). In developing such a strategy, the *mindset* refers to individuals' thought processes, while the *skillset* delves into their abilities, talents, and expertise. The *Toolset* pertains to the tangible and conceptual methods used to execute tasks, and the *dataset* encompasses the structured data essential for decision-making (Fleisher, 2021).

However, our review reveals a salient point that melding these parameters at the individual level is not enough to achieve optimal development for older workers. They should be integrated at the organizational tier as well. Table 2 delves deeper into this alignment, illustrating the essential harmonization for each parameter from the dual perspectives of older workers and the overarching organization.

Fleisher's (2021) mindset, skillset, toolset, and dataset framework were utilized to gain a holistic understanding of individual and organizational attributes necessary for effective aging workforce transformation. Drawing from this, our socio-technical approach emerges as a natural progression. This approach recognizes that optimal organizational performance and well-being are achieved when there is a harmonious integration between the social and technical systems. By understanding the mindset, enhancing the skillset, leveraging the appropriate toolset, and utilizing the relevant dataset, we can effectively address the social dimensions of work while also aligning them with the evolving technological landscape. This integrated view forms the essence of our socio-technical approach, bridging individual and technological capacities for a more cohesive and productive learning and work environment.

Ashworth (2006) used a socio-technical system approach to understand the impact of consequences of labor turnover due to retirement. We extended this idea and the knowledge gathered from this literature review to propose a method for understanding and enhancing older workers' learning in an organization (Fig. 7). A socio-technical system emphasizes integrating workers' social attributes with technical attributes for the best of the system; a joint optimization of both sets of attributes avoids costly tradeoffs in large systems that impede performance (Fox, 1995). We believe that a socio-technical system can serve as a theoretical lens for analyzing organizational needs systematically and foster a supportive and inclusive learning environment for an aging workforce. The proposed approach considers the interplay between social and technical aspects of an organization, recognizing their interconnections and influence on learning outcomes and allowing them to implement strategies that leverage the strengths of the aging workforce while incorporating and utilizing new technologies. This

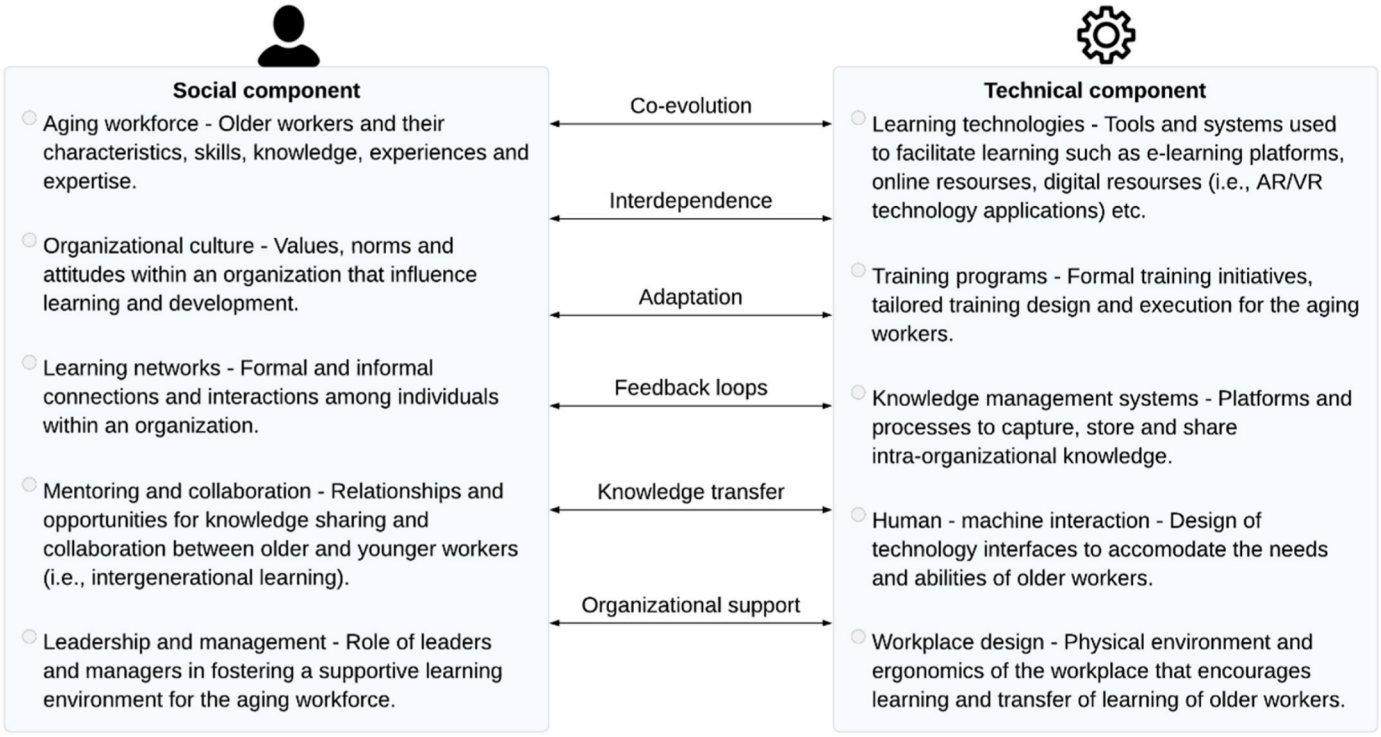

Fig. 7. Key aspects of social and technical components and their interrelations in the context of the socio-technical system for optimizing learning of the aging workforce.

ultimately contributes to the professional growth and job satisfaction of older workers and organizational performance, as outlined by the fourth level of the conceptual framework discussed in Section 2. Fig. 7 illustrates the five key aspects we prioritized by focusing on social component analysis: the aging workforce, organizational culture, learning networks, mentoring and collaboration, and leadership and management. The technical component of the system describes five key aspects: learning technologies, training programs, knowledge management systems, human-machine interaction, and workplace design. The relationships between social and technical components are co-evolution, interdependence, adaptation, feedback loops, knowledge transfer, and organizational support. The social and technical system components evolve together, influenced by each other. A system must continuously adapt to the changing learning needs and preferences of the aging workforce and technological advancements. Therefore, continuous feedback loops between the social and technical components that assess the effectiveness of learning programs and make improvements are essential. The interaction between the social and technical attributes must facilitate the transfer of knowledge and expertise between older and younger workers. This interaction requires organizational support in allocating resources for learning and development initiatives.

Fig. 8 illustrates the proposed two-phase approach for implementing needs analysis, design, and execution. Additionally, it incorporates a continuous improvement loop, indicating that the process is iterative and cyclical. The seven steps are described as follows.

6.2. Step 1: analyzing the social component

The first step is to assess the social dynamics within an organization as highlighted in Fig. 7, particularly those related to the aging workforce, including the demographics (e.g., generation distribution), skills, knowledge, experience, and expertise of older workers, and their roles, relationships, and interactions. It is necessary to identify potential barriers or challenges they face in accessing learning opportunities and engaging in continuous skill development within an organization.

Skill or competency mapping and transactive memory networks are potentially useful tools for addressing workforce development. Armstrong (2006) identifies three types of competencies: behavioral, technical, and certified competencies, such as National Vocational Qualifications. Competency frameworks can be developed by systematically assessing and documenting the skills and competencies (e.g., proficiency, multi-skilling, knowledge levels, experience) of older workers, which can help identify skill gaps and facilitate the creation of effective training plans. Jacobs and Washington's (2003) taxonomy for worker development outlines five levels of competence: novice, specialist, experienced specialist, expert, and master. This taxonomy can serve as a valuable framework for competency mapping.

Analyzing the social component can highlight the areas where older workers may need development and pinpoint the skills that should be transferred from older to younger workers. This ensures that knowledge and skills are retained within the group and, subsequently, within the firm, regardless of whether older workers retire, transfer to different departments, or are promoted to management roles. Transactive memory networks refer to the collective knowledge, expertise, and information distribution among workers, with an understanding of who knows what within a group (Wegner, 1987; Ashworth, 2006). Firms that leverage transactive memory networks can systematically identify and document expertise and knowledge distribution, specialization areas, responsibilities, interaction patterns, information-sharing mechanisms, and succession planning strategies for effective knowledge transfer.

6.3. Step 2: analyzing the technical component

The second step is to examine the technical infrastructure and learning systems as highlighted in Fig. 7, including the availability and accessibility of learning technologies, training programs, and resources for older workers. Identifying how technology supports or hinders the learning of an aging workforce will help understand how, for example, user-friendliness, adaptability, and compatibility affect diverse learning needs. Note that different age generations exhibit varying levels of technological literacy, with "digital natives" not necessarily technology-savvy and "digital immigrants" being less proficient (Becker et al., 2012). This discrepancy in technological skills and knowledge among generations is a consequence of the digital divide, as highlighted by Lythreatis et al. (2022). Human-machine interaction considerations would be beneficial in dealing with potential intimidation related to using new technology in older workers, as discussed by Ravichandran et al. (2015).

Considering the nature of a task (i.e., the ratio of cognitive to motor content) is essential when designing workplaces described as digital work environments (Digiesi et al., 2020). It is also noteworthy that older workers in industries where swift technological advancements occur have better productivity than when change is slow (De Grip, 2015).

6.4. Step 3: identifying learning and training needs

Smith et al. (2010) highlighted the importance of customized learning and training for older workers. The third step is to assess the learning needs and preferences of aging workers, considering factors like competency enhancement and development needs of the organization, career goals of the workers, and industry trends that may require upskilling or reskilling. The findings and outcomes of steps 1 and 2 will form the foundation for this step. This comprehensive assessment enables the creation of relevant, engaging, and impactful learning and training programs tailored to their needs.

6.5. Step 4: designing age-inclusive learning strategies

The fourth step integrates social and technical attributes to cater to the learning needs and preferences identified in Steps 1–3. As Salopek

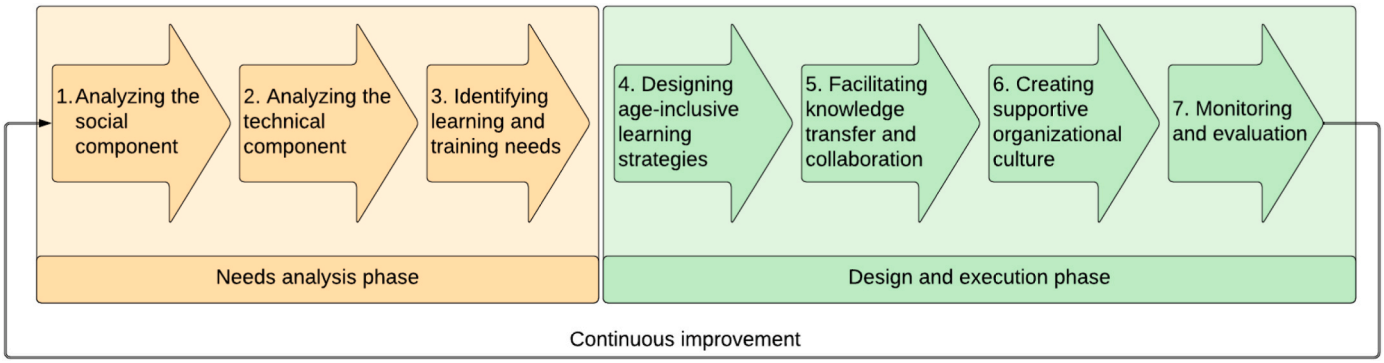

Fig. 8. Socio-technical system approach to improving learning for an aging workforce.

(2000) highlighted, learning styles differ by age (Barrios and Reyes, 2016), which requires tailoring training to workers' traits for effective outcomes. Blended learning methods (e.g., e-learning platforms, mentoring programs, job rotation, job shadowing, and knowledge-sharing platforms) can help accommodate older workers' diverse learning styles and preferences.

It is essential to balance and utilize diverse learning approaches (i.e., formal, informal, and non-formal, as per Findsen, 2015) and maintain shorter gaps between activities to boost learning effectiveness in older workers (Delgoulet and Marquie, 2002). Verneau et al. (2014b) recommended that older workers receive explicit instructions and follow them at their own learning pace. Verworn et al. (2009) suggested hands-on learning techniques to make their learning more effective by integrating the training into their work with error management and multi-level evaluations (Beinicke and Kyndt, 2020). The perception of how relevant and applicable the learning content is to their job and responsibilities can motivate older workers to learn. Using state-of-the-art technologies improves workers' learning and the transfer of this learning to the workplace more effectively than non-interactive conventional methods (Dobrowolski et al., 2021; Forest, 2021).

6.6. Step 5: facilitating knowledge transfer and collaboration

This step focuses on the collaborative diffusion of learning between older and younger workers through mentorship programs, peer learning initiatives, and communities of practice where expertise and experiences are shared and promoted. A collaborative and learning culture helps create a platform to value insights and contributions, thus avoiding ageism and stereotypes (Evans, 2017; Gellert and Kuipers, 2008; Kadefors and Hanse, 2012; Pfrombeck et al., 2023). It is paramount to eliminate age bias in formed groups of older and younger workers, as that halts intergenerational relationships and impedes managing groups with diverse and unique skills and knowledge, thus negatively affecting group members' roles and responsibilities (Brooke and Taylor, 2005). Factors contributing to the success of intergenerational learning activities include workers' intentions to share knowledge, attitudes toward peers, anticipated benefits or threats, knowledge self-efficacy, voluntary nature of participation, duration of the activities, support from professional institutes, task complexity, and clarity of the learning outcomes. Opportunities to apply newly acquired knowledge in the presence of effective leadership and peer support significantly contribute to the successful transfer of learning from training programs to the workplace (Gerpott et al., 2016).

Einstein and McDaniel (1990) cautioned against the potential loss of retrospective memory with age, encouraging firms to take strategic actions to preserve the accumulated knowledge of older workers. Wikstrom et al. (2018) emphasized that the retention of older workers' *tacit knowledge* should be iteratively integrated into daily interactions and collaborative events among young and older workers. The nature of the knowledge receiver, the frequency and nature of the task, and the type of knowledge shared should be considered when managing the transfer of knowledge from older to younger workers (Dixon, 2000; Guvernator and Ernesto, 2020). Beyond just transferring tacit knowledge, collaborative learning across different age groups is essential. It fosters the exchange of ideas, perspectives, and work ethics, contributing to a more inclusive, understanding, and cohesive workplace culture (Wrobel-Lachowska et al., 2018).

6.7. Step 6: creating a supportive organizational culture

Upgrading or modernizing the skills of aging workers relies on an organizational culture that fosters lifelong learning and older workers' experiences and wisdom. Recognizing and rewarding individuals who engage in learning and knowledge-sharing motivates participants to be receptive to positive criticism that guarantees the continuous improvement of the system.

Guerrazzi (2014) noted that investing in training older workers is vital, regardless of firm size. An aging workforce can ensure participation and reach valuable learning outcomes by implementing flexible work patterns, providing challenging tasks, and fostering a learning community (Beck, 2014; Findsen, 2015). What motivates older workers' participation are factors like financial incentives, job satisfaction, and their work's cultural and historical context (Migliore, 2015). These factors also support them emotionally and physically, as firms benefit from their profound experiences (Ng and Law, 2014).

Another important factor is creating age-friendly learning and working environments to address the needs of older workers. For example, Schwerha et al. (2007) recommended avoiding irrelevant auditory and visual stimuli on the production floor to help older workers efficiently learn new assembly tasks. Organizations that create an environment conducive to the learning needs of older workers will contribute to their continuous growth and development and boost their morale, self-worth, and confidence. It demonstrates an organization's commitment to valuing the contributions and potential of older workers and creating a positive and inclusive culture that benefits all.

Organizational culture creates an atmosphere that assists older workers in unleashing their learning potential (Hall and Mirvis, 1995; Roβnagel et al., 2009). Older workers usually use different learning strategies (self-planning, self-regulation, and self-evaluation) to link newly acquired knowledge to residual ones to achieve their performance goals. Older workers also tend to defer retirement when they view their work as challenging and dynamic, as this could benefit them in retirement should they decide to pursue another career postretirement (Unson and Richardson, 2013; Furunes et al., 2015; Eppler-Hattab, 2021).

6.8. Step 7: monitoring, evaluation, and continuous improvement

Implementing mechanisms to monitor and evaluate the impact of learning interventions on the aging workforce using feedback loops and performance metrics is essential to assess their effectiveness, identify areas for improvement, and make necessary adjustments (Güttel et al., 2009). Moreover, the continuous collection of insights from other stakeholders of an organization to ensure the ongoing relevance and adaptability of learning strategies is also crucial.

When considering the juxtaposition between strategic parameters and the socio-technical system approach in understanding older workers and organizational structures, several parallels emerge. Step 1, the social component, primarily emphasizes the mindsets of older workers by focusing on their values, beliefs, attitudes, and relationships. Meanwhile, Step 6, which examines organizational culture, reflects the organization's mindset by emphasizing the importance of continuous learning, valuing older workers, and promoting an inclusive culture.

For skillsets, Step 1 covers competency mapping and worker development, addressing workers' abilities. Step 5, which emphasizes knowledge transfer, highlights the organization's capacity to enable skill-sharing, offer training, and oversee age-diverse teams.

Step 1 caters to older workers' toolsets including their expertise and tacit knowledge. Steps 2 and 4, the technical component, and age-inclusive learning strategies, respectively, concentrate on how the organization supplies user-friendly, age-inclusive tools, technologies, and platforms.

Steps 3 and 7, identifying needs and monitoring and evaluation, respectively, encompass both worker-level and organizational datasets. They showcase the organization's efforts to gather, scrutinize, and utilize data to understand workforce demographics, customize learning programs, measure learning outcomes, and assess the efficacy of interventions.

7. Conclusions and scope for future research

7.1. Main insights

This study systematically reviewed 51 articles on the learning of older workers in the manufacturing and service industries to answer three research questions: (1) What factors influence learning among older workers? (2) What are the learning approaches most effective for them? and (3) How can the learning process of older workers be enhanced?

We discussed the factors influencing the learning of aging workers and categorized them into individual, organizational, and societal factors. Individual factors include personal attributes and preferences that influence the learning process. Organizational factors relate to the workplace environment and support the structures in place. Societal factors represent broader cultural and organizational policy determinants. These three dimensions intertwine and interact, creating a complex backdrop against which learning takes place.

This review also emphasized integrating lifelong learning, technological advancements, and digital learning solutions with intergenerational learning. These approaches are seen as interconnected, each reinforcing and enabling the others. Lifelong learning promotes continuous adaptation, technological advancements unlock new learning avenues, and intergenerational learning fosters collaborative learning diffusion.

Finally, we proposed an approach to enhance learning for the aging workforce by utilizing a socio-technical system perspective. It consists of seven steps: (1) analyzing the social component, (2) analyzing the technical component, (2) identifying the learning and training needs, (3) designing age-inclusive learning strategies, (4) facilitating knowledge transfer and collaboration, (5) creating a supportive culture, (6) monitoring and evaluation, and (7) continuous improvement. This approach provides a holistic model, considering not only the technological tools but also the human, organizational, and societal elements that play a crucial role in the learning process, which will lead to improvements in key areas, such as job performance and productivity, increased job satisfaction and engagement, career development and employability, and health and well-being implications.

We provided a comprehensive reference list in Table A1 in the Appendix, specifically designed to be a valuable resource for practitioners. The table is intended to facilitate easy access to essential literature relevant to each phase of the socio-technical system approach, aimed at enhancing learning among an aging workforce. Importantly, the list extends beyond the literature sourced from our sample and includes additional references that focus on improving worker learning in various contexts, although not exclusively targeting older workers. These supplemental references are conveniently summarized in the "Further Insights" column of Table A1. This column also encompasses related works from diverse contexts, elaborated upon in Section 7.2.

7.2. Future research directions

7.2.1. Learning styles and preferences of older workers

It is highly recommended to empirically investigate different learning styles and preferences by age group, and how to use that knowledge to tailor to their training and professional development programs. Individual variability in processing times and learning rates are critical to overall system performance (Ranasinghe et al., 2023b) and even forgetting rates, particularly among workers of different age groups, may pose challenges for production planning and optimization. It will be valuable to develop analytical models and simulation models that incorporate modified learning curves for groups of workers of different ages performing manufacturing jobs for better production and operations management decisions (for a meta-analysis of learning curves and production economics, see Grosse et al., 2015). Analytical models would likely focus on deriving equations or formulas that can quantify the impact of age on learning rates and subsequent task performance. These models might use empirical data to establish relationships between age, learning rate, and efficiency. Simulation models such as DES models, on the other hand, would replicate the manufacturing processes in a virtual environment and allow managers to see the effects of workers' learning curves over time. These simulations can incorporate variables such as age, experience, and the introduction of new technologies or processes. They can also test different scenarios, like workforce restructuring or training programs, to observe potential outcomes without the need to disrupt actual production.

Age-associated cognitive decline, experience levels, task characteristics (e.g., cognitive versus motor elements), degree of integrated automation or assistive technologies, and digital literacy are some of the potential factors to consider in learning performance and the dynamics of skill acquisition within diverse age groups. It would be interesting to conduct controlled experiments in laboratory settings to study how learning curve parameters (initial processing time and learning rate) differ between two groups of workers differentiated by age (young and old), with the hope of finding a relationship, e.g., between the learning rate and human characteristics, such as age. It would be significant to have two types of tasks, manual and digitally assisted, and find how digital technology impacts the learning curve parameters. Workforce flexibility and cross-training, in this context, cannot be ignored, as forgetting impedes performance.

I4.0-based technologies can support different learning styles and preferences and help tailor training and professional development programs. For example, IoT devices collect real-time data, which is analyzed to determine performance measures for learning progress, performance metrics, and interaction patterns (Ranasinghe et al., 2023a). This analysis helps identify patterns, correlations, and trends related to learning effectiveness and the impact of different factors on learning outcomes. Accurate performance measures are deemed valuable when gaining insights into older workers' learning styles and identifying their personalized learning approaches. Research in this area is limited, and more work is needed.

7.2.2. Technology adoption and adaptation of older workers

Empirical research must focus on how organizations can effectively introduce and implement new technologies that support learning for older workers by accounting for their diverse technological skills and preferences.

Our study concludes that there is a need for a deeper understanding of the barriers/factors that hinder technology adoption and older workers' adaptation to that technology. In designing an effective training program that will deliver desired learning outcomes for older workers, these factors should be considered: their cognitive abilities, digital literacy's perceived usefulness, ease of use, attitudes toward technology, and concerns related to privacy and security. Following training, a firm should continue to assess/monitor the effects of technology on job performance, satisfaction, and well-being.

User interface design facilitates technology adoption and adaptation, particularly for older workers; however, little research is available on understanding how interface design factors (e.g., font size, color schemes, navigation, etc.) affect that. Favorable design principles should facilitate technology adoption and optimize the learning outcomes for older workers (Salvendy and Karwowski, 2021).

7.2.3. Age-friendly learning environments

Our study also concludes that there is a need to investigate how the design and development of age-friendly learning environments can address older workers' specific needs. Optimizing the physical and virtual learning spaces to support older workers is necessary to address those needs. Investigating the impact of technology on knowledge acquisition, skill development, and transfer of learning to the workplace is also needed. VR and AR technologies create immersive and interactive learning experiences that can be customized to match the preferences of

older workers (Dobrowolski et al., 2021; Forest, 2021). These technologies simulate the workplace where older workers practice and acquire skills in a safe and controlled setting. More research is needed on utilizing and optimizing VR and AR applications with visual cues, instructions, and real-time feedback to understand how training older workers can be effective and engaging.

I4.0 technologies, like online platforms and mobile applications, enhance training scalability and accessibility for older workers, supporting self-paced learning. IoT devices can connect with these platforms for real-time progress tracking and personalized recommendations, dynamically adjusting content, methods, and pace to individual needs (Ranasinghe et al., 2023a). If an IoT device detects a struggle with a concept, the program can auto-provide additional resources or personalized coaching. This approach is promising for enhancing the learning experience of older workers.

Gamification techniques offer a promising avenue for making learning more engaging and enjoyable for older workers. Grünewald et al. (2019) explored the psychology of gamification and highlighted its potential benefits in enhancing learning, knowledge retention, application, and overall motivation within an organizational context. They underscored that effective gamification in workplace learning should extend beyond mere play. It needs to align with business objectives and produce measurable outcomes to ensure genuine engagement. Incorporating game elements such as leaderboards, badges, and rewards can spur older workers to actively engage in training. Additionally, this approach aids in knowledge retention and reinforces learning through tools like interactive quizzes, simulations, and scenario-based modules. Thus, future studies should emphasize integrating gamification techniques tailored to the learning needs of older workers.

Mandeville (2022) demonstrated that learning interventions aimed at enhancing workers' metacognitive skills (the ability to reflect on and understand one's learning process) can bolster their self-regulated learning. Therefore, exploring how technology can aid in developing metacognitive skills among older workers, such as designing digital tools and platforms that promote self-reflection and self-directed learning, is a promising avenue for future research.

Artificial Intelligence (AI) has become an integral part of today's industry, revolutionizing processes, enhancing efficiency, and paving the way for human-machine collaboration. Woolf et al. (2020) proposed leveraging intelligent tutoring systems and comprehensive worker data analysis across various fields to craft effective and scalable training solutions for manufacturing workers. Similarly, Wang et al. (2020) introduced an AI-assisted platform designed to train these workers. This platform collects data from both machines and workers and employs AI to scrutinize detailed trainee movements. It offers training in robot/-cobot interaction and utilizes mixed reality for an immersive learning experience. However, the literature concerning the specific needs of older workers is limited. Tapping into AI to address the unique challenges and opportunities of an aging workforce represents a promising avenue for future research. Envisioned solutions include AI-driven training modules tailored to the distinct learning needs of older workers, platforms powered by AI to support intergenerational knowledge transfer, and AI-driven tools that offer personalized performance management and progression routes aligned with their career aspirations and abilities.

7.2.4. Cross-cultural perspectives

As global interactions intensify, increased migration has led to a multigenerational and multicultural workforce in many developed nations. Fan et al. (2021) examined expatriate management from a human resource management perspective, emphasizing it as a continuous learning journey. This journey pushes individuals to comprehend local cultures and norms and modify their assumptions and behaviors for effective cross-cultural communication. Hence, investigating the cultural factors that influence older workers' learning and development remains an untapped research avenue. Future studies could delve into the challenges and strategies to enhance cross-cultural understanding, minimize communication barriers, and encourage effective teamwork among employees from varied cultural backgrounds. Moreover, understanding how cultural values, norms, and expectations influence the learning experiences and outcomes of older workers can provide insights into optimizing learning in such diverse environments.

7.2.5. Long-term impact of effective learning for the aging workforce

There is a need for longitudinal studies to examine the long-term effectiveness and achievement of learning outcomes for an aging workforce. Measures such as job performance and well-being are necessary to assess these aspects. Tracking those outcomes over a long period will help understand the sustained benefits of age-friendly training and professional development efforts.

7.3. Limitations

This study has a few limitations. We could have omitted relevant keywords during the database search. Using only two dominant research databases may have resulted in us missing some relevant literature, with the hope that cross-referencing would compensate for this drawback. However, this review provides a valuable contribution by offering a thorough and unique analysis and synthesis of existing knowledge on the learning of older workers in the manufacturing and service industries.

CRediT authorship contribution statement

Thilini Ranasinghe: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Eric H. Grosse:** Conceptualization, Project administration, Resources, Supervision, Validation, Writing – review & editing, Methodology. **Christoph H. Glock:** Validation, Writing – review & editing. **Mohamad Y. Jaber:** Validation, Writing – review & editing, Resources.

Data availability

No data was used for the research described in the article.

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Appendix

Appendix A

Full keyword search query from Web of Science.
TS = ("ageing" OR "aging" OR "older" OR "senior*" OR "elder*" OR "tenure")
AND.
TS = ("worker*" OR "workforce" OR "employee*" OR "operator*" OR "labor*" OR "labour*")
AND.
TS = ("learning" OR "learning curve" OR "learning function" OR "learning effect*" OR "experience curve" OR "startup curve" OR "forgetting curve" OR "forgetting function" OR "memory loss function" OR "relearning function" OR "re-learning function" OR "progress function" OR "startup function" OR "startup management")
AND.
TS = ("manufact*" OR "industr*" OR "production" OR "assembly" OR "process" or "service")
NOT.
TS = ("machine learning" OR "deep learning" OR "nursing" OR "care" OR "clinical" OR "brain" OR "neuro*" OR "medic*" OR "bank*" OR "teach*" OR "school" OR "student*" OR "education" OR "children" OR "infant*" OR "rat" OR "rats" OR "*bee*" OR "mice")
AND English (Languages) AND Article (Document types)

Table A.1
Further reading: A summary of the literature on the socio-technical system approach of improving learning for an aging workforce specifically relevant for practitioners

Steps of the socio-technical system approach	Resources from the literature sample	Further insights
Step 1: Analyzing the social component	Ashworth (2006)	Armstrong (2006) Jacobs and Washington (2003) Wegner (1987)
Step 2: Analyzing the technical component	Becker et al. (2012) Ravichandran et al. (2015) Digiesi et al. (2020) De Grip (2015)	Lythreatis et al. (2022) Salvendy and Karwowski (2021)
Step 3: Identifying learning and training needs	Smith et al. (2010)	Ranasinghe et al. (2023a)
Step 4: Designing age-inclusive learning strategies	Salopek (2000) Findsen (2015) Delgoulet and Marquie (2002) Verneau et al. (2014b) Verworn et al. (2009) Beinicke and Kyndt (2020) Dobrowolski et al. (2021) Forest (2021) Hall and Mirvis (1995)	Barrios and Reyes (2016) Grünewald et al. (2019) Mandeville (2022) Woolf et al. (2020) Wang et al. (2020) Ranasinghe et al. (2023a)
Step 5: Facilitating knowledge transfer and collaboration	Evans (2017) Gellert and Kuipers (2008) Kadefors and Hanse (2012) Brooke and Taylor (2005) Gerpott et al. (2016) Einstein and McDaniel (1990) Wikstrom et al. (2018) Guvernator and Ernesto (2020) Pfrombeck et al. (2023)	Dixon (2000)
Step 6: Creating a supportive organizational culture	Guerrazzi (2014) Beck (2014) Findsen (2015) Migliore (2015) Ng and Law (2014) Schwerha et al. (2007) Roβnagel et al. (2009) Unson and Richardson (2013) Furunes et al. (2015) Eppler-Hattab (2021)	Fan et al. (2021)
Step 7: Monitoring, evaluation, and continuous improvement	Güttel et al. (2009)	Ranasinghe et al. (2023a)

Table A.2
Classification of the literature sample based on the framework

Literature sample	Individual factors			Organizational factors			Societal factors		Lifelong learning	Technological advancements and digital learning solutions	Intergenerational learning
	Physical and cognitive capabilities	Attitudes and beliefs regarding learning	Perceived relevance and applicability of learning	Learning environment and culture	Support for continuous learning	Availability of training programs	Age-related stereotypes and biases	Social attitudes toward older workers			
Abubakar and Wang (2018)	✓										
Abubakar and Wang (2019)	✓										
Ashworth (2006)				✓	✓		✓				✓
Beck (2014)				✓	✓	✓	✓	✓	✓		
Becker et al. (2012)		✓			✓				✓	✓	
Behie and Henwood (2017)				✓		✓					✓
Beinicke and Kyndt (2020)			✓	✓	✓	✓			✓	✓	
Bercovici and Bercovici (2019)				✓	✓		✓	✓	✓	✓	
Brooke and Taylor (2005)				✓			✓	✓	✓	✓	✓
Cox and Overbey (2022)				✓		✓	✓				✓
Czaja and Drury (1981)			✓								
De Grip (2015)				✓		✓			✓	✓	
De Grip et al. (2015)	✓								✓		
Delgoulet and Marquie (2002)		✓		✓	✓	✓	✓	✓			
Digiesi et al. (2020)	✓										
Dobrowolski et al. (2021)						✓	✓			✓	
Einstein and McDaniel (1990)	✓										
Eppler-Hattab (2021)		✓	✓	✓	✓				✓		
Evans (2017)				✓		✓				✓	✓
Findsen (2015)				✓	✓	✓	✓	✓	✓		
Forest (2021)				✓		✓			✓	✓	
Furunes et al. (2015)		✓		✓			✓		✓		
Gellert and Kuipers (2008)		✓		✓		✓	✓	✓			✓
Gerpott et al. (2016)		✓		✓	✓	✓	✓	✓			✓
Grah et al. (2019)		✓							✓		
Guerrazzi (2014)				✓		✓			✓		
Güttel et al. (2009)				✓	✓	✓			✓		
Guvernator and Ernesto (2020)				✓		✓					✓
Hall et al. (2022)	✓										
Hall and Mirvis (1995)		✓		✓	✓	✓			✓		

(*continued on next page*)

Table A.2 (*continued*)

Literature sample	Individual factors			Organizational factors			Societal factors		Lifelong learning	Technological advancements and digital learning solutions	Intergenerational learning
	Physical and cognitive capabilities	Attitudes and beliefs regarding learning	Perceived relevance and applicability of learning	Learning environment and culture	Support for continuous learning	Availability of training programs	Age-related stereotypes and biases	Social attitudes toward older workers			
Ilmarinen (2001)	✓										
Kadefors and Hanse (2012)					✓		✓	✓			
Migliore (2015)	✓	✓	✓	✓					✓		
Ng and Law (2014)				✓	✓	✓	✓	✓	✓		
Nunes and Kramer (2009)	✓			✓							
Pfrombeck et al. (2023)				✓			✓	✓	✓		✓
Polat and Yılmaz (2020)		✓		✓	✓						✓
Ravichandran et al. (2015)				✓	✓	✓			✓	✓	
Roβnagel et al. (2009)		✓		✓	✓	✓			✓		
Salopek (2000)					✓	✓	✓				✓
Schwerha et al. (2007)				✓	✓						
Smith et al. (2010)				✓	✓	✓	✓		✓		
Unson and Richardson (2013)		✓		✓					✓		
Verneau et al. (2014a)				✓	✓						
Verneau et al. (2014b)				✓	✓						
Verworn et al. (2009)			✓	✓	✓	✓			✓	✓	
Volkoff and Pueyo (2005)	✓			✓							
Wiker et al. (2006)				✓	✓						
Wikstrom et al. (2018)				✓		✓					✓
Wrobel-Lachowska et al. (2018)				✓						✓	✓
Žnidaršič et al. (2021)		✓	✓						✓		

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