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Lack of verified Inclusive Technology for Workers with disabilities in industry 4.0: a systematic review

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ABSTRACT
Technologies from Industry 4.0 enhance human skills and capabilities in production. These advanced manufacturing and digital technologies unlock opportunities to integrate individuals with unique abilities into industrial environments, helping to attain social sustainability. However, the validation process with end-users in real-world manufacturing tasks ensures the technology is robust and aligned with individual needs. However, the topic is in its early stages, and only a few papers concerning validation have emerged in journals. This paper presents a systematic review utilising the PRISMA methodology to examine validated technologies proposed to empower differently-abled workers in the manufacturing sector. The supporting technologies were identified and sorted into four categories: collaborative robots, augmented reality, assistive technology, and gamification. Within the reviewed papers, quantitative and qualitative evidence emerged, showcasing how individuals with challenges proficiently employed technology to complete assembly tasks, elevate their working speed, and reduce the error rate. Nevertheless, there remains a lack of information concerning usability, intuitiveness, and ergonomic considerations. Furthermore, there's an ongoing requirement for long-term studies, standardised methodologies, and statistical assessments conducted by a representative cross-section of participants. Beyond its influence on organisational social responsibility, this research aims to transcend the realm of cultivating a potential new workforce for manufacturing companies.

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KEYWORDS
Enabling technology; disability; manufacturing; workers; inclusion; industry 4.0

1. Introduction

Industry 4.0 (I4.0) transformed traditional manufacturing into more efficient, interconnected, and intelligent systems. The Fourth Industrial Revolution is a concept that originated in Germany in 2011 to describe a high-tech digitised industrial model (Kagermann et al. 2013), based on key technologies such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), Big Data Analytics, Artificial Intelligence (AI), Additive Manufacturing, Augmented Reality (AR), Robotics, and Cloud-Based Systems. These technologies enable 'smart factories', which merge humans, machines, and products in modern production environments that enhance sustainability in economic and environmental aspects (Neumann et al. 2021).

The I4.0 technological advancements aim to reshape job roles through automation, empowering individuals to reach their full potential and address more complex problems. This aligns the workforce with the requirements of a highly advanced industry. In addition, I4.0 emphasises human-machine collaboration over replacement, recognising the human qualities of intelligence, creativity, flexibility, decision-making abilities, problem-solving skills, empathy, and complex cognitive capabilities. These human characteristics are irreplaceable, and I4.0 presents an opportunity for workers to become the smart and flexible components of the manufacturing process (Peruzzini, Grandi, and Pellicciari 2020). This anthropocentric perspective, highlighted by (Sgarbossa et al. 2020), aims to establish more sustainable operational processes. As introduced by (Romero et al. 2016), the human-centred approach envisions the concept of 'Operator 4.0' (04.0) collaborating with enabling technologies in smart factory environments, fostering the integration of apprentices, senior workers, or workers with impairments in industrial processes.

Despite the undeniable significance of the I4.0 technology in the workplace, it is imperative to address the evolving needs of the workforce by promoting inclusive workplaces and ensuring equal opportunities for everyone in a rapidly changing world. In recent times, there has been a growing recognition of the significance of social sustainability, aiming to ensure equitable sharing of the benefits of economic growth and environmental improvements, especially for vulnerable and marginalised groups. Nevertheless, there is a noticeable lack of innovation in assistive technologies tailored for workers with impairments. Disabilities are prevalent and closely related to human diversity; however, individuals with diverse abilities often encounter discrimination in employment and wage disparities due to misconceptions about their capabilities (Boman et al. 2015). Consequently, they face economic challenges, negative attitudes, social exclusion, isolation (Babik and Gardner 2021), and lower life satisfaction (Daley, Phipps, and Branscombe 2018).

Prioritising the integration of workers with challenges into technological advancements and workplace environments is not only a matter of social justice and ethical responsibility but

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also a strategic move with positive economic implications. According to the International Labour Organization (ILO), over 1.3 billion people, about 16% of the world's population, currently live with some disability, with the majority in the working-age range (WHO 2024). Projections suggest this number will nearly double to 2 billion by 2050. The World Health Organization (WHO) reveals that individuals with different abilities face higher risks of poverty and social exclusion (30% vs 21.5%), and women with challenges aged 20–64 experience significantly elevated unemployment rates compared to those without disabilities (18.8% vs 10.6%) (ILO 2019b). Combating discrimination and addressing unequal treatment is crucial for advancing social justice on a global scale.

Differently-abled individuals are highlighted in the United Nations (UN)' 2030 Agenda and its Sustainable Development Goals (SDGs), explicitly mentioned in seven targets and eleven indicators across education, economic growth, employment, inequality, and universal accessibility (DESA 2023). As the world enters the latter half of the journey towards SDGs achievement, there is a call for contributions to tackle global challenges with a long-term vision. The Disability Inclusion Strategy (UN 2019), introduced by the UN, incorporates a rights-based approach for individuals facing impairments. As the envisioned level of inclusion has not been reached, efforts and investments need to be intensified to ensure the comprehensive inclusion and meaningful participation of the global population with disabilities.

In terms of economic implications, an increasing number of organisations recognise disability as a source of diversity and innovation (ILO 2023a). This perspective provides enhanced opportunities for persons with disabilities as both consumers and employees, contributing to a more equitable and prosperous society. Enterprises globally acknowledge the ethical and economic imperative of integrating workers with different abilities into their workforce, policies, and operations. Consequently, companies of all sizes are now actively moving towards impactful and enduring disability inclusion, particularly in employment, leading to enhanced business practices that benefit all stakeholders involved. In this context, the global challenge of the Future of Work (ILO 2019a) highlights the urgent need to establish human-centred and inclusive workplaces, ensuring that no one is left behind. At this moment, it is imperative to address inequalities faced by individuals with impairments to prevent the future of work from replicating the past.

The primary objective of this research is to review and verify the applicability of I4.0 technology in supporting differently-abled workers, highlighting existing gaps and barriers. Also, it aims to inspire further research and innovation in megatrends that will shape the future of work. Additionally, the research seeks to educate stakeholders on the capabilities of workers with diverse abilities and advocate for inclusive work environments. Therefore, the research questions are as follows: What existing I4.0 technologies have been verified for supporting differently-abled workers in manufacturing tasks? 2) How are current I4.0 technologies integrated into manufacturing to accommodate the diverse abilities of workers facing challenges? 3) What considerations are essential for enhancing the participation and representation of individuals with diverse abilities in the workforce, particularly in the context of Industry 4.0?

This review explores the expectations surrounding I4.0 and its potential for ensuring the equitable sharing of the benefits of economic growth and environmental improvements, especially among vulnerable and marginalised groups. Despite these expectations, there is currently a lack of clear evidence supporting this idea. Consequently, this study makes a unique contribution to the emerging literature in this field, particularly in understanding the impact of I4.0 technologies on differently-abled workers, a topic not yet comprehensively understood, as it raises awareness about the skills of workers with diverse abilities. A systematic literature review can shed light on potential challenges, ethical concerns, and areas where improvements are needed. Finally, identifying relevant contributions in the existing literature provides insights into areas where further research is needed, such as the transition from Industry 4.0 to the emerging paradigm of Industry 5.0 (I5.0) (Müller and Commission, E., for Research, D.-G., Innovation 2020). This contribution can orient future research initiatives, helping researchers focus on specific aspects that require attention and exploration.

In accordance with the research questions, Section 2 offers a descriptive literature analysis within the field, followed by an exposition of the current state of the art of technology in Section 3. Section 4 subsequently delves into an examination of the workers' impact, culminating in Section 5 with a discourse on potential avenues and future orientations.

2. Identification of relevant concepts

This section focuses on presenting findings derived from prior reviews related to the topic to offer a comprehensive context and integrate other insights into the synthesis. The examined papers have contributed significantly to this review, introducing important concepts related to sustainability and social advances in I4.0, besides the emerging paradigm of I5.0.

2.1. Insights on other reviews

In the domain of I4.0 assistive technology (Goodley et al. 2020), provide a speculative and conceptual review that underscores the intersection of disability and new technologies, particularly within the context of inclusive education for individuals with impairments in I4.0. Their review explores potential interactions between disabilities and emerging technologies, highlighting speculative possibilities. Notably, the authors identify a literature gap concerning the participation of people with impairments in I4.0. Additionally (Mark et al. 2019), explore the potential inclusion of people with unique abilities in I4.0, providing insights into legal foundations and restrictions across three European countries. They also introduce worker assistance systems from I4.0, designed to make jobs accessible for individuals facing mental or physical challenges in the manufacturing sector.

Moreover, the integration of digitalisation and circularity is discussed by (Viles et al. 2022) as a means to enhance sustainability efficiency and resilience in the industry. In another comprehensive review (Mark, Rauch, and Matt 2021b), focus on promising technologies within the domain of worker assistance systems in manufacturing. They remark on the importance of implementing and utilising such systems for companies to gain advantages in production and enhance employee well-being. The categorisation of these systems into sensorial, cognitive, and physical categories, initially proposed by (Romero et al. 2016), is subsequently utilised by (Mark et al. 2021) for presenting a structured grouping of technologies, as presented in Table 1. This classification shows a relation between people's impairments and possible solutions offered by technologies. However, there is little evidence concerning the validation by end-users of these technologies.

Finally (Bonello, Francalanza, and Refalo 2024), presented a review regarding the design of workstations for operators with disabilities within the context of I5.0. Their focus is on identifying research works related to workstation design, I5.0, sustainability, and disability. Despite the author's identified potential sustainability solutions, the industry still faces challenges in the implementation. The authors stress the need for collaboration between academia and industry for further opportunities on the shop floor within the context of I5.0.

While (Bonello, Francalanza, and Refalo 2024) provides a valuable and comprehensive revision of theoretical aspects related to workstation design for people with disabilities, the authors express concerns about the technology's insufficient focus in long-term studies, robust testing, worker feedback, and methodologies for assessing the user experiences. Furthermore, they propose future research directions for workstation design that go beyond merely onboarding assistive technologies to include assessing the learning progress, well-being, and productivity of operators with disabilities over time.

This review addresses and expands upon the concerns raised by (Bonello, Francalanza, and Refalo 2024), placing particular emphasis on technological solutions and their practical applicability in real-world scenarios. Rather than merely presenting theoretical designs, this review delves into experiences that contribute to a deeper understanding of the validation processes for I4.0 technology involving the end-users. The resulting validation significantly enhances the credibility of the proposed solutions. Moreover, this review presents insights into the real-world applicability for bridging the gap between theoretical designs and their practical implementation.

Table 1. Identified assistance systems for production by (Mark et al. 2021).

Type	Assistance System
Sensorial (extend sensing capabilities)	Eye Tracking Galvanic Skin Response (GRS) Physiological Sensor – Heart Rate (HR) Intelligent Hand Tracking RGB Camera Motion Tracking and Gesture Recognition device Smart Watch Wearable Tracker Haptic Glove Infrared Camera Portable Vibration Device Position Tracking System
Physical (extend physical capabilities)	Exoskeleton Arm Support Leg Support Back Support Flexible Assembly Assist Robot Robots/Automats Telemanipulator/Balancer/Lifting Aid Wearable lifting/Holding Aid Ergonomic Manual Workplaces Robot Assistance System with ToF Camera Collaborative Robots
Cognitive (extend cognitive capabilities like "orient" or "decide")	Augmented Reality (AR) Virtual Reality (VR) Mixed Reality (MR) Tablet Visual Computing System Projection-Based Assistance System Head Mounted/Display (HMD) Smart Scan Glove Smart Phone In-situ Projection Laser Projection System Portable Computer Computer Assisted instruction (CAI) Projector Monitor Pictorial Instruction Voice Control AI Based Intelligent Personal Assistant

2.2. Sustainability aspects from I4.0

The Fourth Revolution is characterised by the creation, exchange, and distribution of economic, political, and social value, driven fundamentally by emerging technologies. It holds the potential to enhance our quality of life and elevate global income levels. However (Beier, Niehoff, and Hoffmann 2021), conducted a review on the sustainability concept of I4.0 and its ties to the SDGs. The study revealed numerous expectations but found limited evidence supporting this connection. While the industry focuses predominantly on economic aspects such as growth and productivity, there is no clear indication that I4.0 leads to more sustainable production. The review suggests that I4.0 might operate similarly to traditional methods but in a digital format, making it hard to fulfil the SDGs. Furthermore (Caiado et al. 2022), depic I4.0 as a structural revolution for operations and supply management, offering efficiency and productivity improvements. Nonetheless, uncertainties persist regarding the integration of advantages and consolidated benefits with the SDGs, highlighting challenges related to society, employability, and various inequalities and risks.

Additionally (Beier et al. 2020), argue that sustainability aspects are not inherently integral to the I4.0 concept but are treated as 'add-on features'. Consequently, these aspects are not thoroughly researched, and potential benefits remain unidentified. The authors recommended that researchers in the field of I4.0 should focus on demonstrating specific economic, environmental, and societal benefits and provide evidence of the concept's implementation effects on sustainable development in diverse contexts.

2.3. The new paradigm I5.0

The I5.0 paradigm, formulated by the European Commission (EC), advocates for a sustainable, human-centric, and resilient European industry (Breque et al. 2021). Unlike a mere technology advance, I5.0 represents a comprehensive perspective on the I4.0 approach, introducing regenerative purposes and guiding principles to the evolution of industrial production (Eric et al. 2023) identified various drawbacks and weaknesses in I4.0, promoting the exploration of new research directions. These include the crucial need to validate the interaction between humans and technology, consider worker diversity factors, and a broader range of capability levels. Furthermore, the focus needs to extend beyond physical aspects to encompass the psychosocial effects of technology usage and interactions between humans and technology. This underscores the necessity for advanced consideration of human factors during the transition from I4.0 to I5.0, addressing issues such as mental exhaustion, reduced job satisfaction, and stress.

In addition (Gladysz et al. 2023), highlights the lack of human-factors integration in I4.0, emphasising the immature phase of O4.0 (Romero et al. 2016) and the need for technical studies to materialise the current technical concept (Zizic et al. 2022) establish a connection matrix between I4.0 and I5.0 manufacturing companies, with a focus on human-centricity, sustainability, resilience, people, organisation, and technology. Another review by (Mourtzis, Angelopoulos, and Panopoulos 2022) points out the system/machine-oriented nature of I4.0, contrasting it with the human-centric approach in I5.0. The authors argue for considering I5.0 as a framework that enables the coexistence of industry with emerging societal trends and needs.

Regarding applications within the new I5.0 paradigm (Grosse 2023), explores future opportunities for human interaction with technology in manual order picking in warehouses, highlighting the need for further research. However, this exploration is limited to warehouses and does not address disability issues. Finally (Battini et al. 2022), presents a job rotation scheduling model considering socio-technical factors, incorporating elements of I5.0 for a sustainable, human-centric, and resilient industry, acknowledging the challenge posed by a diverse workforce.

3. Methodology

3.1. Literature research and material selection

The review has followed the PRISMA methodology (Page et al. 2021) and the methodology proposed by (Webster and Watson 2002). A search was conducted in Scopus and Web of Science (WoS) using the following strategy:

(1) ('Assistive technology' OR 'Industry 4.0' OR 'worker assistance' OR 'Assistive systems' OR 'enabling Technology') AND (production OR assembly OR manufactur* OR fabrication OR workshop OR factory OR shelter*) AND (disabilit* OR impair* OR disable*) AND (worker* OR people OR person) AND (inclusion OR empower*)

Only English-language articles focusing on the fields of engineering, computer science, and manufacturing within the time frame of 2013 to 2023 were considered. A total of 104 entries were found in two databases. The screening process involved reviewing the titles to identify those related to the intersection of manufacturing and assistive technology for individuals with special needs. Subsequently, abstracts were examined to identify experimental testing details, while papers related to rehabilitation and home assistive devices were excluded. The selected papers then underwent a comprehensive review to identify both qualitative and quantitative evidence from the technology evaluation. Papers were excluded if the proposed technology lacked experimental validation or had no end-user involvement. To expand the research, *go backward* citation tracking and *go forward* searching, following the approach by (Webster and Watson 2002), was conducted. This additional search led to the discovery of more documents, resulting in a total of 23 papers. Figure 1 illustrates the literature search strategy.

3.2. Descriptive analysis

3.2.1. Publications by year and type

While the number of collected papers may be reduced, it remains a notable accomplishment for research groups that have conducted technology assessments involving individuals with diverse abilities. The collected papers encompassed a range of research conducted over nearly a decade; however, contributions on the topic were not released yearly, as presented by Figure 2(a). The first proposal using in-situ projection was presented in 2013 by (Korn, Schmidt, and Hörz 2013). There was a lack of publications in the field from 2017 and 2018 until there were published two conference papers in 2019 (Aksu, Jenderny, Kroll, et al. 2019; Aksu, Jenderny, Martinetz, et al. 2019) and a journal paper (Kildal et al. 2019). A potential reason behind that gap can be

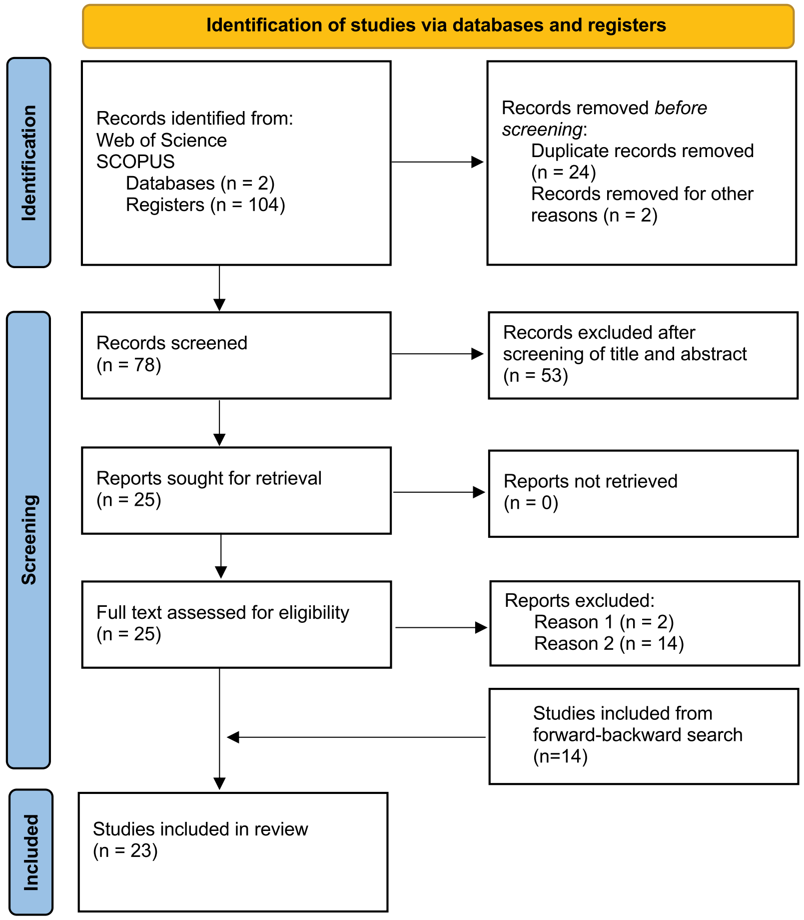


Figure 1. PRISMA methodology followed for the screening process.

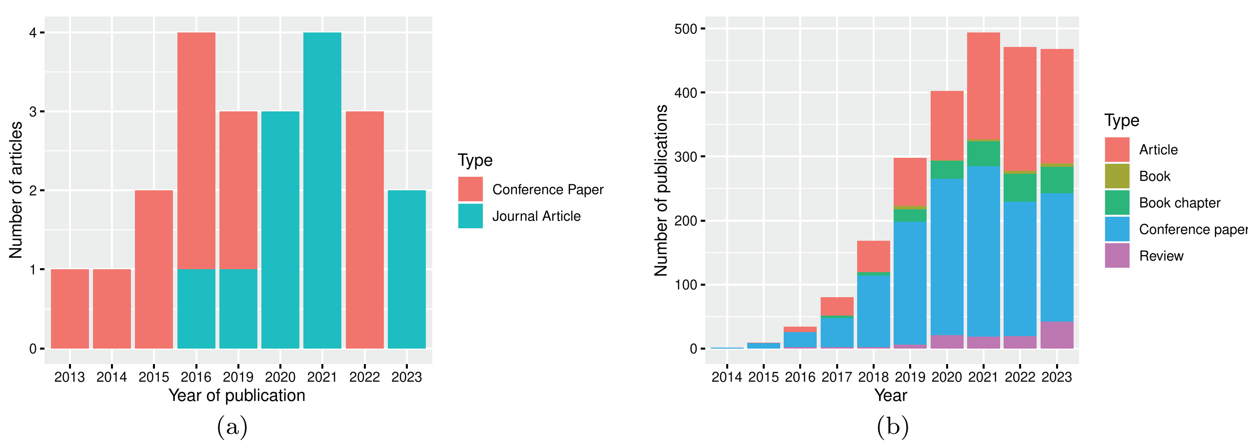
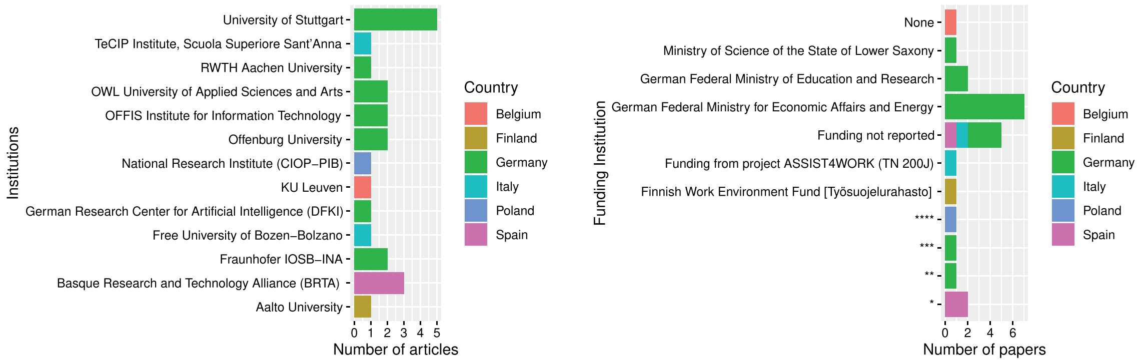


Figure 2. Number of publications by year and the type of paper. (a) Selected papers. (b) Publications regarding robots in I4.0.

limited funding, as research papers developed from 2014 to 2016 reported the same grant (01MT12021E) provided by the German Federal Ministry for Economic Affairs and Energy. As of 2023, only two additional studies have been reported in journals by (Drolshagen, Pfingsthorn, and Hein 2023; Peltokorpi et al. 2023). To highlight the scarcity of publications on the evaluation of technology for differently-abled workers, Figure 2(b) depicts a graph of publications in the same time frame related to robots in Industry 4.0.

3.2.2. *Papers by country and affiliation*

Most studies were conducted in German institutions, as shown in Figure 3(a). Several factors may have contributed to this trend. Initially, the German government's Industry 4.0 initiative, designed to integrate digital and flexible tools for the development of human-centred production systems, likely played a significant role in stimulating research endeavours in this field (Mark et al. 2019). Also, the German government requires employers to hire at least 5% of differently-abled



(a) (b)

Figure 3. (a) Institutions and countries researching the topic. (b) Funding organizations and countries: (*) European Union's Horizon 2020 Research and Innovation Programme (**) Stiftung Wohlfahrtspflege NRW, Landschaftsverband Rheinland, caritasverband fur die Stadt Koln e.V. (***) Manufacturing R&D Department of the OFFIS Institute for Information Technology in Oldenburg (****) Ministry of Science and Higher Education/National Centre for Research and Development.

workers; thus, they are continuously searching for solutions to avoid high fees in cases of law infringements (Drolshagen et al. 2020). Despite Italy, Poland, and Spain also implementing quotas (7%, 6%, and 2%, respectively), Germany stands out due to its compensatory levy system for severe disability non-compliance. Employers failing to meet those obligations in Germany are subject to a levy, with the redirected funds benefiting companies and departments actively employing or creating jobs for such individuals (Thornton 1998). Consequently, this incentivises German funding institutions to actively support research and development projects in this specific field, as shown by the comparison presented in Figure 3(b). Regarding Sheltered Workshops and organisations that collaborated with research papers, Figure 4(a) presents the distribution by country.

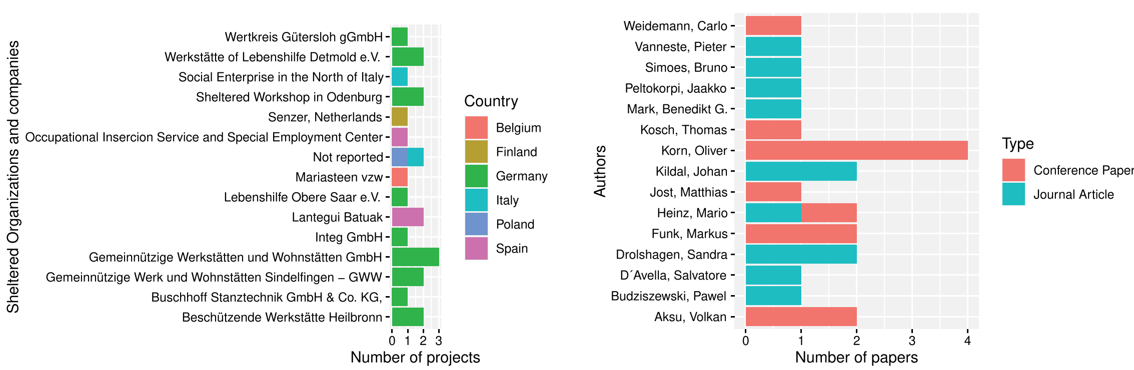
3.2.3. *Publications by author and number of citations*

It was common to find more than one publication from the same author, initially as preliminary findings in conference proceedings and subsequently as expanded articles in journal publications. This iterative approach allowed authors to present their research in stages, providing early insights and more comprehensive studies in later publications. Figure 4(b) presents the primary authors and the type of contribution. Furthermore, it is observed that the contributions published in journals are nearly equivalent to those presented in conferences, indicating a transition towards more extensive and formal dissemination of the research.

The 10 most cited papers are detailed in Table 2. Notably (Funk et al. 2015), and (Funk, Mayer, and Schmidt 2015) are the most cited, constituting 39.3% of the total citations. These contributions have attracted significant attention due to their exploration of a groundbreaking topic. They employed a well-structured approach, comparing in-situ instructions from an assistive system against pictorial instructions for product assembly in a workplace. Both studies involved several workers with impairments during evaluation and applied rigorous statistical methodologies for results extraction. The high citation counts for these papers are partly attributed to shared authorship, leveraging the authors' reputation. In contrast, older papers like (Korn, Schmidt, and Hörz 2013) have fewer citations, likely because they focused on presenting early results of a demonstrative assembly process.

4. Findings on validated technologies from I4.0 for supporting differently-abled workers in manufacturing

This section elucidates the findings in the compelled papers concerning the evaluation of technology by



(a) (b)

Figure 4. (a) Sheltered workshops and organizations which collaborated with research papers. (b) Number of publications by author and type.

Table 2. Ten Most cited contributions.

Reference	Title	Citations
Funk et al. (2015)	Comparing projected in-situ feedback at the manual assembly workplace with impaired workers	85
(Funk, Mayer, and Schmidt 2015)	Using In-Situ Projection to Support Cognitively Impaired Workers at the Workplace	85
(Kosch et al. 2016)	Comparing Tactile, Auditory, and Visual Assembly Error-Feedback for Workers with Cognitive Impairments	49
(Korn, Schmidt, and Hörz 2013)	Augmented manufacturing: a study with impaired persons on assistive systems using in-situ projection	42
(Vanneste et al. 2020)	Cognitive support for assembly operations by means of augmented reality: an exploratory study	34
(Korn et al. 2014)	Context-aware assistive systems at the workplace: analysing the effects of projection and gamification	33
(Kildal et al. 2019)	Empowering assembly workers with cognitive disabilities by working with collaborative robots: a study to capture design requirements	25
(Budziszewski et al. 2016)	Workstations for people with disabilities: an example of a virtual reality approach	13
(Drolshagen et al. 2020)	Acceptance of Industrial Collaborative Robots by People With Disabilities in Sheltered Workshops	11
(Heinz et al. 2021)	Dynamic Task Allocation based on Individual Abilities – Experiences from Developing and Operating an Inclusive Assembly Line for Workers With and Without Disabilities	9

individuals facing various types of challenges. The validation of technology is a crucial process that ensures the effectiveness, accessibility, and user-friendliness of the proposed solutions. Involving end-users is essential to ensure that the proposal not only meets technical requirements but also offers practical support in real-world scenarios. The validation process yields valuable insights into the user experience, enabling developers to comprehend how individuals with diverse abilities engage with the proposed technology. Furthermore emphasis on real-world applicability ensures that the solutions are not just theoretically sound but are also pragmatic, functional, and pertinent to the genuine challenges encountered by workers with disabilities in their everyday tasks. Additionally, validation helps to identify the specific needs and preferences of individuals, empowering developers to customise the technology to address individual challenges effectively and ensure that it provides meaningful support.

4.1. Technology classification and description

According to the collected papers, the validated technologies could be categorised as collaborative robots (Cobots), Augmented Reality (AR), Assistive Technologies (AT) and Gamification, as shown in Table 3.

4.1.1. Collaborative robots

Robotic arms with grippers were proposed as enabling technology in manufacturing tasks. In the study by (D'Avella and Tripicchio 2020), a user interface displays images of 10 objects in a cluttered environment. Individuals with physical impairments identify and select a desired object by clicking on the image, prompting a two-arm robot to grab it. Another study (Drolshagen et al. 2020), involves 10 workers with physical and cognitive needs collaborating with a robotic arm. The robot handles small wooden sticks while the operator verifies their size. Additionally (Kildal et al. 2019, 2021), introduce a two-arm robot to assist workers with impairments in assembling electric cabinets. The robot, equipped with a laser beam, highlights connectors for the human operator to wire. It also conducts quality tests by visually inspecting cables and performing continuity tests in the connectors. In (Weidemann et al. 2022), a workstation equipped with a robotic arm helps workers with mobility limitations to perform a quality inspection for sheet metal parts manufactured. The robot picks parts from a bin and transports them in front of the participant for visual inspection. In cases where the worker is unable to perform the piece manipulation, the robot takes charge in accordance with joystick commands. Moreover, the study conducted by (Drolshagen, Pfingsthorn, and Hein 2023) involves the utilisation of an industrial robotic arm equipped with a gripper. This robotic system offers six pointing gestures to provide support to

Table 3. References classified by technology.

Technology	References employing the category.
Collaborative Robots. *Cobots are designed to work alongside humans, assisting with physically demanding or repetitive tasks. They can be programmed to adapt to the specific needs and capabilities of individuals with challenges, enabling them to participate in manufacturing processes actively.*	(D'Avella and Tripicchio 2020; Drolshagen et al. 2020; Drolshagen, Pfingsthorn, and Hein 2023; Kildal et al. 2019, 2021; Weidemann et al. 2022)
Assistive Technology. *Assistive tools and specialized software to enhance the worker's abilities and support individuals with diverse abilities, enabling them to perform tasks effectively and safely in manufacturing.*	(Aksu, Jenderny, Kroll, et al. 2019; Aksu, Jenderny, Martinetz, et al. 2019; Budziszewski et al. 2016; D'Avella and Tripicchio 2020; Drolshagen, Pfingsthorn, and Hein 2023; Funk et al. 2015; Funk, Mayer, and Schmidt 2015; Heinz et al. 2021; Heinz-Jakobs, Große-Coosmann, and Röcker 2022; Jost et al. 2022; Kildal et al. 2021; Korn, Schmidt, and Hörz 2013; Kosch et al. 2016; Mark, Rauch, and Matt 2021a; Simões et al. 2021; Weidemann et al. 2022)
Augmented Reality. *This technology can enhance accessibility by overlaying digital information and instructions onto the physical environment. This can help people with special needs to navigate the workspace, operate machinery, and access relevant information, besides improving their efficiency and safety.*	(Funk et al. 2015; Funk, Mayer, and Schmidt 2015; Heinz et al. 2021) (HeinzJakobs et al., Heinz-Jakobs, Große-Coosmann, and Röcker 2022), (Jost et al. 2022; Korn, Schmidt, and Hörz 2013; Peltokorpi et al. 2023; Simões et al. 2021; Vanneste et al. 2020)
Gamification. *It is a concept that involves incorporating game elements into non-game contexts to enhance engagement, motivation, and learning. Even though Gamification is not specifically categorized as a technology from I4.0, it can be applied within the same framework.*	(Korn et al. 2014; Korn, Lang, et al. 2016; Korn, Schmidt, and Hörz 2013; Korn, Tso, et al. 2016)

workers requiring assistance during the assembly of various Lego constrictions, each comprising eight bricks.

As outlined by (Mark, Rauch, and Matt 2021b; Späker, Mark, and Rauch 2021), various robotic features can extend workers' physical capabilities, including flexible assembly robots, telemanipulators, lifting aids, wearable machines, exoskeletons, and back support. In addressing different abilities, pre-I4.0 technologies have been tested for assisting workers with physical impairments in lifting and moving heavy objects within factories (Chang et al. 2005; Kang, Kim, and Chung 2008). Moreover, other proposals include mobile assistant robots for industrial applications (Drust et al. 2013), approaches integrating human-hybrid robots to support assembly tasks (Weidner, Kong, and Wulfsberg 2013), and systems to enhance human-robot collaboration (Mueller et al. 2014; Ramer and Franke 2014). However, there is a demand for a new generation of cobots equipped with high-performance sensors controlled by smart systems and advanced software, operating collaboratively with humans without safety fences. Recent approaches to this challenge include lean thinking (Stadnicka and Antonelli 2019) and decision support systems (Gjeldum et al. 2022). Meanwhile (Weidemann et al. 2023), highlights the utilisation of cobots and discusses essential considerations regarding interaction, interfaces, role distributions, safety, ergonomics, and health associated with the deployment of these robots in industrial settings. Finally (Mandischer, Gürtler, Weidemann, Hüsing, Bezrucav, Gossen, and Corves 2023), proposes a generalised approach focused on using collaborative robots to include differently-abled people in workplaces.

4.1.2. Augmented reality (AR)

Sheltered work organisations aid non-reading workers by employing pictorial instructions, visually representing the assembly process as an alternative to textual guidance. These visual instructions are placed directly on material boxes, guiding individuals through tasks. Recently, an emerging trend involves using projection technology for augmentation, displaying assembly instructions and step-by-step guidance directly onto the workspace. Also, the projector highlights material boxes (pick-by-light), displays pictograms, workflow elements, and intermediate assembly stages, and assists in visualising crucial aspects like assembly parts' position and orientation. This can help people with special needs to navigate the workspace, operate machinery, and access relevant information, besides improving their efficiency and safety.

For example (Korn, Schmidt, and Hörz 2013), compares traditional monitor-based instructions with augmented workplace projection displaying assembly pieces in 1:1 scale. In (Funk et al. 2015), in-situ projection is employed to display various visualisations (pictorial, video, and contour instructions) for picking and placing components in a machine. Similarly (Funk, Mayer, and Schmidt 2015), uses in-situ projection to demonstrate that workers with neurodiverse conditions can assemble complex products using Lego block constructions (Heinz et al. 2021) utilises interactive projections for assembling electronic components into a PCB, displaying step-by-step instructions, graphic overlays, animations, and markers for component boxes. In the study by (Vanneste et al. 2020), oral, paper, and spatial augmented reality instructions were employed in three assembly tasks involving participants with cognitive and motor disabilities. In (Jost et al. 2022), PARTAS (Personalizable Augmented-Reality-based Task Adaptation System) integrates a projector to project contour-based instructions and a pick-by-projection assistant into the working space (Simões et al. 2021) introduces an ergonomic workstation augmented with projected visual information (videos showing the actions to be performed, interactive diagrams, 3D virtual explanations, spatial augmentation for pointing the components and the boxes containing materials), aiding participants in comprehending precise cable connections (Heinz-Jakobs, Große-Coosmann, and Röcker 2022) presents an assembly guidance system using projection with interactive instructions, including text, images, video, and coloured overlays for each step, along with highlighting component boxes. In their research (Peltokorpi et al. 2023), investigated the impact of four instruction formats (paper-based, animations, projection, and adaptative projection) on individuals categorised by three types of disabilities (illiterate – unable to read, psychosocial – sensitive to stress, cognitive – intellectual issues or slow learning).

Table 4 presents a comparison between traditional display methods and AR alternatives found in research projects.

Although AR has the potential to improve industrial settings, several challenges must be addressed. These include the implementation costs, which involve necessary hardware and software development. Additionally, training in AR systems can be intricate, emphasising the importance of proper training for effective utilisation. Hardware-related challenges, such as limited battery life, connectivity issues, and compatibility problems, also need consideration. Furthermore, specific industries may face regulatory challenges associated with the adoption of AR technology.

Table 4. Comparison between methods for displaying instructions in the workplace.

Augmented Reality	Other traditional display methods (pictorial, video)
Projects contextual information onto the physical workspace, displaying information within the context of the immediate surroundings.	Presents information on a separate screen or printed material without a direct connection to the user's environment.
Offers options for interacting with digital content while keeping hands free for physical tasks.	Require users to hold printed materials or interact with a separate device.
Offers a more immersive experience by integrating digital content into the workspace, thereby improving user engagement and comprehension.	While video displays pre-recorded content, its real-time interaction capabilities are limited.
In-situ projection provides flexibility in situations where users need to move freely without obstructing the workspace.	Requires a direct line of sight for the user to view the information.
It can be very effective in education and training, allowing one to learn and practice skills in an immersive environment.	These systems are more passive and less interactive.

4.1.3. Assistive technologies

Assistive technology encompasses devices, equipment, or systems designed to enhance the functional capabilities of differently-abled individuals. Its primary aim is enabling individuals to perform tasks that might otherwise be challenging due to physical, cognitive, sensory, or communication impairments. In human-centred production, technology is harnessed to empower and support workers, striving to create work environments that optimise synergy between humans and machines, fostering efficiency, productivity, and overall well-being. Table 5 summarises the assistive technology reviewed in the papers.

Integrating assistive technology into manufacturing systems enhances the capabilities and independence of differently-abled employees. Beyond incorporating in-situ projection for training, there are other systems that have been integrated into customised workstations. For instance, hardware and software are used to monitor the worker's activity and assembly speed, motion recognition and activity recognition modules, error-detection systems for providing feedback to the workers during the assembly, and alternative interfaces for machine interaction. Other systems can incorporate assistive technology to support workers with sensory impairments; for example, visual alerts can be replaced with tactile or auditory signals to notify workers of critical information. Furthermore, customised workstations with adjustable height and accessible controls to accommodate individuals with diverse physical abilities.

4.1.4. Gamification

Gamification (Deterding et al. 2011) shows promise in supporting workers with cognitive impairments, enhancing workflow efficiency, and illustrating real-time visualisations of production progress. For instance (Korn et al. 2014), implemented a gamification tool in a production environment integrated into a customised workstation. This tool resembles a Tetris-style puzzle game representing the work process, where the colour of the bricks changes according to the worker's assembly speed, providing visual feedback. Another implementation by (Korn, Lang, et al. 2016) involves a Pyramid game design projected into the working space alongside assembly steps. It uses motion detection for automated time measurements and real-time error detection, dynamically changing the pyramid's colour based on the worker's progress. The design also includes a human figure climbing the pyramid, and a trophy cup is awarded for completing the assembly without mistakes. Additionally, the specialised gamified software called GATRAS (Games to Train and Assess Impaired Persons) was developed to assess the abilities of persons with cognitive impairments and compared to generic tools in (Korn, Tso, et al. 2016).

Although there is limited evidence regarding long-term effects, potential consequences associated with gamification exist, with variations depending on the system's context and specific goals of implementation. For instance, Gamification has been noted to enhance user engagement and motivate workers to persist in activities (Mitchell, Schuster, and Jin 2020). Additionally, it influences and enhances skills and learning through continuous engagement, increasing motivation and productivity by making activities more enjoyable and rewarding. However, to remain effective, gamified systems may require ongoing adaptation. Regular updates to game mechanics, challenges, and rewards can sustain interest and engagement (Ponce et al. 2020). Continuous evaluation and interaction based on user feedback are crucial for long-term effectiveness. Gamified systems frequently collect user data, offering insights into the users' preferences. Over time, this data can be analysed to refine and optimise gamification elements, enhancing user engagement and satisfaction (Méndez et al. 2022).

The potential appeal of gamification spans various age groups, yet its effectiveness is influenced by factors like the nature of the gamified experience, the target audience, and individual preferences. While gamification tends to resonate with younger audiences who generally enjoy interactive and game-like experiences (Oprescu, Jones, and Katsikitis 2014), its effectiveness for adults and professionals depends on alignment with their specific goals and preferences (Bell, Toorn, and Isaias 2020).

4.2. Developed activities and its relevance to the manufacturing environment

The proposed activities aimed to benefit differently-abled workers in assembling real products like shears, clamps, jewellery boxes, electronic boards, and electric cabinets, besides other demonstrative products using Lego blocks and puzzles. Table 6 provides a brief overview of the manufacturing activities enhanced in research projects.

The proposed activities exposed the workers to diverse assembly challenges. This variety helps them to develop a versatile skill set that can be applied across different manufacturing scenarios, such as the assembly of metal products in (Funk et al. 2015; Korn, Lang, et al. 2016; Mark, Rauch, and Matt 2021a). Working on real products provides a level of familiarity with the types of items and

Table 5. Assistive technology used in references.

Description	References
Motion recognition	(Drolshagen, Pfingsthorn, and Hein 2023; Funk, Mayer, and Schmidt 2015; Jost et al. 2022; Kildal et al. 2021; Korn et al. 2014; Korn, Schmidt, and Hörz 2013; Kosch et al. 2016, 2016)
Automatic quality control	(Drolshagen, Pfingsthorn, and Hein 2023; Funk, Mayer, and Schmidt 2015; Jost et al. 2022; Kildal et al. 2021; Korn et al. 2014; Korn, Schmidt, and Hörz 2013; Kosch et al. 2016, 2016)
Error detection and feedback	(Aksu, Jenderny, Kroll, et al. 2019; Kosch et al. 2016)
Specialised software and apps	(Aksu, Jenderny, Martinetz, et al. 2019; Budziszewski et al. 2016; Drolshagen, Pfingsthorn, and Hein 2023; Weidemann et al. 2022)
Artificial vision and object recognition	(D'Avella and Tripicchio 2020)
Alternative interfaces	(Kildal et al. 2021; Mark, Rauch, and Matt 2021a; Simões et al. 2021)
Object recognition	(D'Avella and Tripicchio 2020; Mark, Rauch, and Matt 2021a)

Table 6. Activity description in the manufacturing environment.

Reference	Production process
(Aksu, Jenderny, Kroll, et al. 2019)	Assembling high-quality boxes for jewellery in three stages (cutting, gluing, and folding).
(Aksu, Jenderny, Martinetz, et al. 2019)	Changing a broken drill head on an industrial machine.
(D'Avella and Tripicchio 2020)	Perform human-robot collaboration for order picking in cluttered environments.
(Drolshagen et al. 2020)	Collaborating with a robot arm to check the size of small wooden sticks.
(Funk et al. 2015)	Perform the workflow of picking and inserting five parts in a machine for producing a clamp.
(Funk, Mayer, and Schmidt 2015)	Perform assembly tasks utilising Lego pieces at a manual workplace.
(Heinz et al. 2021)	An assembly process of THTa components, small upright PCBb and cable adapters.
(Heinz-Jakobs, Große-Coosmann, and Röcker 2022)	Perform four assembly tasks for demonstrative products with different complexity levels.
(Jost et al. 2022)	Manual picking and packaging tasks with increasing difficulty levels.
(Kildal et al. 2019, 2021)	Collaborate with a robot to wire terminals during the assembly process of electric cabinets.
(Korn et al. 2014; Korn, Schmidt, and Hörz 2013)	Assemble eight identical car undercarriage using nine Lego bricks.
(Korn, Lang, et al. 2016)	Manually assembling metal shears in five steps.
(Korn, Tso, et al. 2016)	Manual assembly of a metal shear in nine steps.
(Kosch et al. 2016)	Assembly demonstrative tasks using Lego Duplo pieces with different complexity levels.
(Mark, Rauch, and Matt 2021a)	Manual assembly process of 10 tasks.
(Simões et al. 2021)	Wiring an electric cabinet in a real-world scenario.
(Weidemann et al. 2022)	Visual quality inspection task of metal parts.
(Peltokorpi et al. 2023)	The adjuster of a car seat product consisting of three subassemblies and 17 parts to be assembled.
(Vanneste et al. 2020)	Assembly of three manual tasks by steps involving the connection of wires, quality control, and placing wires, wheels, screws, and rings.
(Budziszewski et al. 2016)	Placing parts at a workstation for grinding spring faces.
(Drolshagen, Pfingsthorn, and Hein 2023)	Assemble Lego constructions of eight pieces.

[a]Through-Hole Technology, [b]printed circuit board.

tools commonly produced in a manufacturing setting, as the cases presented by (Aksu, Jenderny, Kroll, et al. 2019; Budziszewski et al. 2016; Heinz et al. 2021; Peltokorpi et al. 2023). Besides, assembling demonstrative products can provide training to follow instructions, adaptability, and problem-solving as shown by (Drolshagen, Pfingsthorn, and Hein 2023; Funk, Mayer, and Schmidt 2015; Heinz-Jakobs, Große-Coosmann, and Röcker 2022; Korn et al. 2014; Korn, Schmidt, and Hörz 2013), which are fundamental skills in the shop floor. By engaging in the customised workstation for assembling real and demonstrative products, workers with challenges can be familiarised with incoming technologies such as robotic arms, automatic quality control, and interfaces with machines, which are valuable skills necessary in manufacturing (D'Avella and Tripicchio 2020; Drolshagen et al. 2020; Kildal et al. 2019, 2021; Vanneste et al. 2020). Finally, activities related to repetitive tasks, visual quality inspection, and object classification are relevant for industrial processes as humans adapt easily to changing requirements of industrial processes (Aksu, Jenderny, Martinetz, et al. 2019; Jost et al. 2022; Weidemann et al. 2022). To summarise, some skills that can be important for the shop floor are:

- Creativity to solve problems and to address new challenges.
- Adaptability to changing production requirements or unexpected situations.
- Complex decision-making requires human intuition, judgement, and emotional intelligence.
- Dexterity in manufacturing processes requires fine motor skills and touch.
- Handling unstructured environments in dynamic manufacturing facilities.
- Cost effective for small-scale or customised production.
- Natural quality control in products with complex specifications.

4.3. Participants with challenges involved in validation processes

Most of the research projects collaborated with Sheltered Workshops, which are non-profit organisations dedicated to supporting people with diverse abilities in entering the workforce. These workshops tailor activities to accommodate individuals' abilities and needs, fostering personal growth, independence, and workforce integration. Workers from various organisations participated in validating proposed technologies in the papers, as illustrated by Figure 4(a).

Most participants in the studies had previous manufacturing experience, showcasing proficiency in following step-by-step instructions. They were assigned challenging tasks based on their physical or cognitive requirements. Some studies categorised participants into groups based on capacities, skills, ability to memorise, or degree of cognitive impairment. However, only a few papers specified using scores from tools like the 'Werdenfelser Test Battery' (Peterander 2009) or a sheltered workshop score (Korn, Lang, et al. 2016), a performance index (Funk, Mayer, and Schmidt 2015) to group participants according to their abilities and needs. Certainly, measuring cognitive abilities involves assessing various functions to determine the extent of impairment; thus, many authors provided a general description in terms such as 'participants with minor impairment of intelligence' (Aksu, Jenderny, Martinetz, et al. 2019) or terms like 'moderate', 'low cognitive', 'mild disability', or 'severe disability'. Table 7 presents a classification of people with disabilities who participated in the validation studies. Some terms referred to describe the illnesses and limitations of the participants are enlisted in the same Table.

Table 7. The participants' impairments classification according to the description provided by the reference.

Disability	References
Cognitive. *Disruption of social behavior, epilepsy, mental impairments, mental disability, learning disorder, lack of the ability to memorize complex information, mental and intellectual disabilities, illiteracy, psychosocial (sensitivities to stress), slow learning, neurological disabilities.*	(Aksu, Jenderny, Kroll, et al. 2019; Aksu, Jenderny, Martinetz, et al. 2019; Drolshagen et al. 2020; Drolshagen, Pfingsthorn, and Hein 2023; Funk et al. 2015; Funk, Mayer, and Schmidt 2015; Heinz et al. 2021; Heinz-Jakobs, Große-Coosmann, and Röcker 2022; Jost et al. 2022; Kildal et al. 2019, 2021; Korn et al. 2014; Korn, Lang, et al. 2016; Korn, Schmidt, and Hörz 2013; Korn, Tso, et al. 2016; Kosch et al. 2016; Mark, Rauch, and Matt 2021a; Peltokorpi et al. 2023; Simões et al. 2021; Vanneste et al. 2020)
Physical. *Disabilities in the upper limbs, disabilities in the lower limbs, partial paralysis in legs and arms, motor disabilities, limitations in fine motor skills, and restricted trunk, arm, and head movements.*	(Aksu, Jenderny, Kroll, et al. 2019; Budziszewski et al. 2016; D'Avella and Tripicchio 2020; Drolshagen et al. 2020; Simões et al. 2021; Vanneste et al. 2020; Weidemann et al. 2022)
Sensorial. *Visual deficiencies*	(Drolshagen et al. 2020; Jost et al. 2022; Simões et al. 2021)

While most studies included both male and female subjects in varying quantities, not all authors reported this information (see Table 8). Different age groups were also represented, with the youngest participant (16 years old) reported by (Funk et al. 2015) and the oldest (64 years old) by (Heinz et al. 2021). The study with the highest number of participants was (Korn, Schmidt, and Hörz 2013) with 81 participants, followed by (Funk et al. 2015) with 64. Additionally, some researchers involved participants without special needs, such as technicians, supervisors, and physicians, to observe the experiments and provide feedback. However, the reduced number of participants remains as a common limitation in most studies.

4.3.1. Effectiveness of technologies

Educational background holds significance, especially for workers with higher education in technology or specific industries, enhancing their ability to understand and adapt to new technologies. Individuals with strong educational backgrounds often possess well-developed learning skills, making them more receptive to new technologies and capable of understanding complex systems, leading to quicker incorporation of changes in the workflow.

In terms of experience, workers with more years are likely more familiar with industry-specific tools and technologies. Long-term employees often have a deep understanding of workplace processes, requirements, and challenges, making assistive technologies more effective in addressing real-world needs. However, experienced workers with well-established routines may exhibit resistance to changes, even if designed to assist people facing challenges.

Furthermore, the efficacy of technologies for workers facing challenges is influenced by factors extending beyond experience and education. For example, the alignment of technologies with the workflow and routines of the sheltered workshops can be a determinant factor. Also, customisation to meet a diverse range of workers' needs ensures technology compatibility with their capabilities, as shown by (Weidemann et al. 2022). Additionally, the provision of friendly interfaces or adaptive input devices enables individuals with challenges to interact effectively with technology (Kildal et al. 2021; Simões et al. 2021). Therefore, assessing the needs and capabilities of workers is crucial for technology effectiveness, requiring regular evaluations and extracting feedback to address challenges or limitations (Hüsing et al. 2021; Mandischer, Gürtler, Weidemann, Hüsing, Bezrucav, Gossen, Corves, Hüsing, et al. 2023).

4.4. Evaluation metrics and measured variables

The studies provided quantitative and qualitative data to substantiate their findings. These data types elucidated the advantages of the proposed technology and facilitated comparisons to identify its benefits.

Table 8. Number of participants and diversity.

Reference	Number	Male	Female	Min age	Max age	Mean	SD
(Aksu, Jenderny, Kroll, et al. 2019)	5	–	–	20	21	20.6	0.55
(Aksu, Jenderny, Martinetz, et al. 2019)	6	4	2	20	35	27.2	10.34
(D'Avella and Tripicchio 2020)	4	–	–	–	–	–	–
(Drolshagen et al. 2020)	10	7	3	21	60	42.3	13.04
(Funk et al. 2015)	64	41	23	16	59	41.7	10.6
(Funk, Mayer, and Schmidt 2015)	15	11	4	20	55	40.1	10.33
(Heinz et al. 2021)	4	3	1	38	64	5.2	-
(Heinz-Jakobs, Große-Coosmann, and Röcker 2022)	52	33	19	–	–	–	–
(Jost et al. 2022)	8	–	–	–	–	22	–
(Kildal et al. 2021)	5	–	–	–	–	–	–
(Kildal et al. 2019)	1	–	–	–	–	–	–
(Korn et al. 2014)	60	–	–	–	–	–	–
(Korn, Lang, et al. 2016)	5	–	–	–	–	–	–
(Korn, Schmidt, and Hörz 2013)	81	–	–	–	–	–	–
(Korn, Tso, et al. 2016)	20	–	–	–	–	–	–
Kosch et al. (2016)	16	–	–	34	53	40.33	6.36
(Mark, Rauch, and Matt 2021a)	7	5	2	18	40	–	–
(Simões et al. 2021)	20	10	10	–	–	–	–
(Weidemann et al. 2022)	6	4	2	–	–	34	–
(Peltokorpi et al. 2023)	24			–	–	–	–
(Vanneste et al. 2020)	44	24	20	22	58	–	–
(Budziszewski et al. 2016)	2	31	39	–	–	–	–
(Drolshagen, Pfingsthorn, and Hein 2023)	10	5	5	21	59	–	–

[a]Number of participants, [b] Male, [c] Female.

The quantitative measurements indicate the dependent variables, time-to-complete (TCT) and error rate (ER), obtained manually by reviewing the video information or automatically using movement detection hardware. Also, hand-tracking has been used to detect if the participant picked up the right components. Other variables include how many times the user received assistance from supervisors and if the task was successfully completed. Those variables were used as quality values to assess performance, effectiveness, and efficiency. Table 9 summarises the quantitative variables found in research papers.

Regarding the qualitative aspect, the studies predominantly focused on survey applications, which were occasionally completed by participants themselves or, when necessary, by their supervisors due to participants' limitations in responding. Well-known questionnaires were applied as a modified version, such as NASA-TLX (Hart and Staveland 1988) and the System Usability Scale (SUS) (Lewis and Sauro 2009). Furthermore, questionnaires and interviews were simplified to facilitate the evaluation process, utilising Likert scales or scales with limited options. Even "body language" and gestures were also analysed as quantitative feedback (Drolshagen et al. 2020). The quantitative feedback helped reveal the system's mental workload, usability, and intuitiveness. It also provided valuable insights into the system's familiarisation, learnability, satisfaction, acceptance, and openness to the technology, as well as information about emotional experiences and expectations related to the experiments. Table 10 presents the observed quantitative metrics.

4.4.1. Standard metrics for evaluating the impact of technology on workers

To summarise, here is a set of standard metrics that can be universally applied:

- User satisfaction scales or feedback from workers, reflecting the technology's effectiveness and user-friendliness.
- Time taken to complete a specific activity to measure the efficiency of technology in facilitating the task completion.
- Frequency of errors made by workers while using the technology to indicate its effectiveness in minimising errors and ensuring a reliable experience.
- Time and resources required for workers to become proficient in using the technology, to assess the ease of learning and adaptability of the technology.
- Usability testing sessions to provide an insight into specific usability issues and improvement areas.
- Level of engagement or interaction to indicate the technology's ability to keep users engaged.
- Measurement of the impact of technology on the overall productivity of workers with challenges to evaluate whether the technology enhances or hinders productivity in real-world scenarios.

4.5. Perceived impact on workers' well-being, productivity, and skills development

4.5.1. Well being

Well-being refers to the employees' overall happiness and contentment within the context of their work. For instance, incorporating assistive technologies in assembly lines increased satisfaction and independence without raising stress levels of workers with different cognitive abilities (Heinz et al. 2021). Besides, the visual support helped workers with mental challenges to be more confident in performing their assigned tasks (Funk et al. 2015). In (Kildal et al. 2021), the workers with intellectual challenges expressed great satisfaction and profound pride in their accomplished feat. Finally, it was observed that assistive projection empowered workers with cognitive impairments, enabling them to engage in more complex tasks and promoting inclusion (Heinz-Jakobs, Große-Coosmann, and Röcker 2022; Korn, Schmidt, and Hörz 2013).

Table 9. Qualitative metrics.

Quantitative	References
Time on task, task completion time, execution times, mean production time, total assembly time, elapsed times. *How long it took the participant to complete the task*	(Aksu, Jenderny, Kroll, et al. 2019; D'Avella and Tripicchio 2020; Drolshagen, Pfingsthorn, and Hein 2023; Funk et al. 2015; Funk, Mayer, and Schmidt 2015; Korn et al. 2014; Korn, Lang, et al. 2016; Kosch et al. 2016; Simões et al. 2021)
Task success, success rate. *If the participant succeeded or failed the task*	(Aksu, Jenderny, Kroll, et al. 2019; Korn, Schmidt, and Hörz 2013; Simões et al. 2021)
Task accuracy. *The participant solved the task without help.*	(Aksu, Jenderny, Kroll, et al. 2019; Drolshagen, Pfingsthorn, and Hein 2023)
Error rate, amount of errors, average error rate, measured errors. *This variable is related with the number of errors committed by the participant.*	(Drolshagen, Pfingsthorn, and Hein 2023; Funk et al. 2015; Funk, Mayer, and Schmidt 2015; Korn et al. 2014; Korn, Schmidt, and Hörz 2013; Kosch et al. 2016; Simões et al. 2021)

Table 10. Qualitative metrics.

Metric	References
SEA. *Subjectively Perceived Effort Scale*	(Aksu, Jenderny, Kroll, et al. 2019; Aksu, Jenderny, Martinetz, et al. 2019)
SUS. *System Usability Scale*	(Aksu, Jenderny, Kroll, et al. 2019; Heinz et al. 2021; Korn, Schmidt, and Hörz 2013; Simões et al. 2021)
QUESI. *Questionnaire for the Subjective Consequences of Intuitive Use*	(Aksu, Jenderny, Martinetz, et al. 2019)
Opinion from the participants	(Drolshagen et al. 2020; Drolshagen, Pfingsthorn, and Hein 2023; Funk, Mayer, and Schmidt 2015; Jost et al. 2022)
Surveys and interviews with experts	(Heinz et al. 2021; Kildal et al. 2019; Kosch et al. 2016)
Adapted likert-based questionnaires	(Heinz-Jakobs, Große-Coosmann, and Röcker 2022)
Adapted NASA-TLX questionnaire. *Mean perceived task loads*	(Funk et al. 2015; Korn, Lang, et al. 2016; Vanneste et al. 2020)
NPS. *Satisfaction benchmark Net Promoter Score*	(Simões et al. 2021)
Learning curve analysis	(Peltokorpi et al. 2023)

However, well-being is a subjective measure with inherent limitations as it relies on self-assessments, commonly influenced by various factors and social biases; thus, responses may align with societal expectations. Also, well-being is dynamic in nature and can fluctuate over time due to life events or mood variations. In addition, it is personal and not comparable across individuals, as expectations can vary. Finally, individual differences in response styles or communication skills can contribute to variability.

Despite their limitations, subjective well-being measures provide valuable insights when integrated with objective indicators such as physical health, financial security, access to education, and opportunities. Also, considering the context in which assessments are made can enhance the overall understanding of well-being. The authors observed several advantages concerning their physical, mental, and emotional well-being, besides satisfaction and fulfilment with their job and work environment.

4.5.2. Productivity

There were observed advantages that could help to optimise operations on the shop floor, reduce costs, and deliver high-quality products more efficiently. According to (Korn et al. 2014), gamification and in-situ projections contributed to accelerated production rates of workers with cognitive challenges. Similarly, it was shown in (Simões et al. 2021) that the use of augmented information in the workspace helped to lower completion times, reduce missteps, and reduce the workers' mental workload of workers with diverse cognitive and physical abilities. The participants with cognitive challenges improved their performance in process accuracy and success rate by using assistive systems (Mark, Rauch, and Matt 2021a). The feasibility of cooperative workplaces has been demonstrated, offering innovative approaches to divide complex tasks into manageable segments and allocate them among multiple workers with mental and intellectual challenge (Heinz et al. 2021). Each worker suffering cognitive differences can receive personalised workplace setups and instruction styles tailored to their needs, enhancing efficiency and inclusivity (Jost et al. 2022).

4.5.3. Skills development and its long-term impact

The step-by-step assistive technology proved to be highly effective, enabling workers with cognitive differences previously not considered for the job to execute tasks with minimal training (Kildal et al. 2021). Also, the system presented in (Mark, Rauch, and Matt 2021a) the differently-abled workers to express interest in developing additional tasks and exhibiting a strong eagerness to learn new skills. It was shown by (Heinz et al. 2021) that the assistive technology allows workers with cognitive impairments to acquire and develop new skills, leading to heightened job satisfaction and improved career prospects. Similarly, differently-abled workers could execute tasks independently and without requiring continuous supervision (Simões et al. 2021).

Emphasising adaptability and resilience in skills cultivates a workforce capable of navigating evolving job roles and technological advancements. Moreover, ensuring enduring benefits from skills development requires essential policies promoting continuous learning and education. A skilled and flexible workforce drives innovation, competitiveness, and economic resilience, attracting investments and supporting technological advancements for a knowledge-based economy. Also, this skilled workforce facilitates collaboration and interdisciplinary knowledge, contributing to a more versatile workforce. Therefore, industries benefit from this interdisciplinary collaboration, leading to economic diversification and resilience. Additionally, skills that prioritise adaptability, continuous learning, and resilience contribute to a workforce capable of facing evolving job roles and technological changes, better positioning it to handle uncertainties. However, the availability of training infrastructure plays a crucial role in ongoing skill development.

5. Discussion

5.1. The current scenario for differently-abled workers in I4.0

5.1.1. Benefits for individuals with diverse abilities when integrated into the workforce

Integrating people with challenges into the workforce benefits their economic aspect, as it provides a stable income, fosters financial independence, and the ability to cover expenses; thus, their satisfaction and contentment increase. Also, participating in a work environment enhances people's self-esteem and confidence while offering them opportunities to learn new skills and advance their careers. Additionally, interacting with colleagues strengthens their social skills, participation, and leisure activities. In this context, it is presented by (Clube and Tennant 2022) a circular initiative implemented by a company in Vietnam to hire a workforce of persons with cognitive, physical, visual, and hearing impairments to manufacture products using material from excess and stock fabric. That business model satisfies this vulnerable community's fundamental human needs, demonstrating a legitimate social benefit.

5.1.2. Advantages for manufacturing companies in hiring differently-abled employees

The manufacturing sector can benefit from workers with diverse abilities in its workforce, enhancing innovation and problem-solving. As stated in (ILO 2023b), people facing disabilities have been pushed to develop skills such as perseverance, problem-solving, agility, forethought, innovative thinking, and a willingness to experiment in order to adapt to the world around them. A diverse workforce is more likely to consider accessibility features in product design, designing products and services with inclusivity in mind. Thus, they contribute to the development of innovative products, services, and business strategies. Also, if the company advocates for diversity and inclusion, it not only elevates morale but also fosters loyalty among employees. Finally, hiring individuals with diverse abilities aligns with the United Nations' SDG for full employment and decent work.

The industry also recognises that investing in individuals with diverse abilities is not only a socially responsible practice but also a strategic decision that yields positive returns. Tangible benefits in companies employing differently-abled persons, such as profitability (revenues and net income), value creation (economic profit margin), and a reduced turnover in the workforce, have been presented by (ILO 2023b) as key drivers of long-term business success. In addition, tax incentives, wage deductions, and subsidies further contribute to a clear return on investment (Mark et al. 2019).

From the customers' perspective, employing individuals with diverse abilities enhances customer satisfaction, relations, and market reach. Besides, it brings reputational benefits among customers and their families; an inclusion policy generates empathy, improving the company's public image and a positive brand reputation. As indicated by (ILO 2023b), considering persons with disabilities as customers and consumers will also gain the loyalty of their families and immediate environments, increasing the potential disposable income to be spent up to $8.1 trillion.

5.1.3. I4.0 technologies for improving the workers' skills

I4.0 technologies offer various innovations that can be beneficial for improving the skills of workers and differently-abled workers in manufacturing environments. These technologies could contribute to a dynamic and advanced manufacturing environment, empowering workers with enhanced skills. The technologies and their contribution to a more inclusive and skill development environment are outlined next:

- *IoT*. Facilitates device and sensor interconnectivity in manufacturing, enabling real-time data collection and analysis. This technology empowers workers with insights into equipment performance, production status, and quality control, fostering informed decision-making and enhanced problem-solving skills.
- *AR*. Overlays digital information onto the real-world environment, and VR generates immersive, computer-generated environments. In manufacturing, it offers real-time instructions, visual cues, and task-related information to workers. This technology enhances the worker's understanding of the process and execution of complex processes.
- *VR*. Generates immersive, computer-generated environments. In manufacturing, it is used for training simulations, enabling workers to practice tasks in a safe virtual setting. As a benefit, this hands-on experience boosts skills and confidence for real-world tasks.
- *AI*. Algorithms analyse large datasets to identify patterns, optimise processes, and predict issues. In manufacturing, AI aids workers in decision-making, automates tasks, and provides personalised training suggestions. It contributes to enhancing complex decision-making on the shop floor.
- *Robots and Cobots*. Workers collaborate with these robots for tasks demanding precision, strength, or repetition, allowing them to concentrate on more complex cognitive aspects of their work. This technology can assist workers in tasks that require precision and dexterity.
- *Additive Manufacturing*. Enables the production of prototypes and customised components. Workers can develop skills in designing, programming, and operating 3D printers. It promotes creativity and problem-solving abilities in manufacturing.
- *Big Data analytics*. Processes and analyzes large datasets to extract valuable insights. In manufacturing, this aids workers in optimising production processes, identifying areas for improvement, and making data-driven decisions to enhance overall efficiency. This technology helps workers extract actionable insights from large datasets, facilitating strategic decision-making.
- *CPS*. Integrates physical processes with digital systems, providing workers with improved monitoring and control of manufacturing processes. This technology enhances the worker's understanding of the interaction between physical and digital elements.
- *Cloud platforms*. Offer internet-based access to computing resources and data storage. Workers in manufacturing can utilise cloud computing for collaborative projects, data sharing, and real-time information access. It enhances workflow efficiency and decision-making.

5.2. Risks and opportunities

5.2.1. Problems faced by individuals with challenges in the I4.0 era

The technological advancements from I4.0 bring unprecedented opportunities for the inclusion of people with diverse abilities in the world of work. However, there are challenges associated with the working conditions that need to be addressed now. To summarise, there are presented several problems next:

- Fear of unemployment due to replacement by technologies developing repetitive activities. It is important to promote continuous upskilling and reskilling programmes tailored to the needs of individuals facing challenges.
- Limited access to training programmes for preparing individuals for I4.0 roles. To address this fear, close collaboration between institutions, employers, and government agencies is needed to develop inclusive training initiatives.
- Discrimination in the workplace related to the employers' prejudices and stigmas. It is important to create awareness about the capabilities and contributions of people with challenges and their significance to the workforce. There is a need to conduct accessibility assessments in companies to implement accommodations for creating an inclusive workplace.
- Inadequate workplace accommodations or facilities for supporting differently-abled workers.
- Inequality in access to career advancements and promotions. There is a need for promotion systems based on merits and encourage a culture of recognition and reward for diverse talents.

Apart from the need for new skills, discrimination, and technological obstacles, challenges related to working conditions include insufficient and irregular wages and prolonged working hours.

5.2.2. Limitations and challenges of the current technology

The technological revolution is driving significant changes in the labour market, shaping future jobs but also requiring new skills. New job opportunities are emerging while others become obsolete, leading to an increased demand for high-quality jobs and a decline in less-qualified employment. The adaptability of jobs in this evolving landscape is crucial for those individuals already in the workforce.

The technological advancements of I4.0 hold substantial opportunities for people with disabilities if designed inclusively. However, the failure to do so could pose significant threats to the employment prospects of individuals with challenges. For instance, the prevalence of software and I4.0 technologies that lean towards machine orientation may exacerbate these challenges. Addressing these issues requires a concerted effort to advocate for the development and integration of more inclusive workplaces and business models.

Implementing assistive technology for differently-abled workers is a complex process, with challenges related to social factors and effective communication (Ponce et al. 2019). Highlights the risk of disappointment when product design solely focuses on technological advancements. Thus, universal design principles must be considered, involving individuals with disabilities in the innovation process for creating accessible products and services.

While assistive technology offers opportunities in both society and the labour market, ensuring its widespread availability as part of reasonable accommodations provided by employers is crucial. However, people with disabilities face digital exclusion due to affordability and access issues. Disparities in access to the internet and communication technologies between developed and developing countries further exacerbate this problem. To overcome challenges associated with the new skill requirements, technological barriers, and working conditions, there is a need for proactive measures to transform these hurdles into opportunities.

5.2.3. How I4.0 technologies can be adapted to be more inclusive

I4.0 has the potential to enhance inclusivity in various ways by addressing accessibility, and diversity and promoting equal opportunities. In Table There are presented examples describing the technology and how can be used in an inclusive way.

- *Accessible Human-Machine interfaces*. Adapt the user interface to consider diverse needs. For instance, incorporate speech recognition, gesture control recognition, or eye-tracking into manufacturing equipment to make it easier for employees to operate machinery, as shown by (Drolshagen et al. 2020; Kildal et al. 2021).
- *Digital Twins and Virtual Models for Accessibility Design*. Use DT, virtual replicas of physical systems or products, to simulate and optimise accessibility features during the design. For instance, creating a virtual model of a factory floor and simulating the movement of employees with mobility challenges helps to identify potential obstacles in the layout, as shown by (Budziszewski et al. 2016).
- *Inclusive training*. Develop AR or VR training programmes that cater to various learning styles and cognitive capabilities. Employees can choose between visual, auditory, or textual formats based on their needs. AR can be tailored to meet specific needs, such as auditory cues, haptic feedback, and text-to-speech functionalities. Also, different levels of assistance can be considered (Simões et al. 2021).
- *AI-driven assistive technologies*. Develop assistive technologies that support employers with disabilities, including language translation, voice recognition, or image recognition for real-time services needed on the shop floor, such as presented by (Drolshagen, Pfingsthorn, and Hein 2023).
- *Flexible automation for job*. Design automation systems to accommodate different tasks and roles, ensuring that employees with challenges can be integrated into the production process. For instance, implement dynamic workstations with different production line setups, allowing individuals to contribute effectively (Heinz et al. 2021).

5.2.4. Potentially suitable roles for differently-abled workers in I4.0

The technological advancements offer people facing challenges new forms of participation and suitable roles in a new potential workforce. For instance, people with mobility challenges can work in data analytics using adaptive technologies to process, interpret, and manage data. Certainly, AI, machine learning, and data seem to be more in-demand job positions in the coming years. Also, individuals with physical challenges could use proper tools to create software, programme robots, or develop applications that do not necessarily require physical mobility. Using text-to-speech or speech-to-text technology could help people with hearing or speech impairments by providing online support. Individuals with diverse abilities can also control software quality, test applications, and monitor system outputs. In addition, people with mobility challenges can oversee remotely monitored systems using digital interfaces. By using virtual reality (VR) or augmented reality (AR), operators with special needs can train others in various tasks or provide insights based on their expertise. Finally, those persons with neurological differences might offer unique perspectives and problem-solving skills that can be beneficial in Research&Development roles.

5.2.5. Policies to be revised and implemented regarding the employment of differently-abled workers

The global employment landscape for individuals facing challenges varies across countries and regions, requiring supportive policies. Effective employment practices necessitate coordination between government and public institutions (Harris 2017). There are some that must be revised:

- The Article 27 of the UN Convention on the Rights of Persons with Disabilities (CRPD) emphasises equal work

opportunities in an inclusive environment (United Nations 2006).
- The 2030 Agenda for Sustainable Development (DESA 2023) provides reports of the achievements and failures for sustainable development to establish future directions.
- The ILO Centenary Declaration for the Future of Work (ILO 2019a) highlighting the importance of the human-centred approach and the need of equal opportunities for persons with challenges.
- Countries with inclusive policies and anti-discrimination laws, like the U.S. with the Americans with Disabilities Act, tend to achieve better employment rates (ADA 2023).
- Initiatives such as the Rehabilitation Research and Training Center for Disability Inclusive Employment Policy study the employment life cycle (DIEP-RRTC 2022).
- Flexible employment systems at the state and corporate levels are recommended for improved inclusion (Giovanis and Ozdamar 2019)

Besides, industries can adopt inclusive policies to harness the benefits of a diverse workforce. Implementing non-discrimination principles throughout the recruiting and hiring processes, promoting equal employment opportunities, and providing specialised disability awareness training for all employees can foster a supportive work environment, reduce harassment, and create an anti-discrimination culture. Leaders should encourage a culture of inclusion and diversity throughout the organisation. Additionally, staying informed about evolving laws and regulations related to disability employment is crucial for leaders to make necessary adjustments, take advantage of financial benefits, and utilise tax incentives for hiring persons with unique abilities. Regularly revising and updating policies, measuring metrics related to hiring, retention, and advancements of differently-abled workers, and incorporating feedback from workers contribute to the ongoing effectiveness of these policies.

5.3. Research opportunities and directions

5.3.1. Identified gaps in the literature

Researchers can explore key areas to comprehend challenges faced by differently-abled workers and propose innovative solutions. This includes focusing on the long-term impact of assistive technologies, assessing sustainability in skills development, and establishing records of enduring benefits linked to overall well-being.

Also, there is a need for robust long-term studies with workers to evaluate technology usability, intuitiveness, integration, benefits, and acceptance. This information aids in developing new training programmes and providing feedback for technology design. Incorporating workers' feedback into the digital system is essential to avoid over-saturation of the workforce, and determining the level of impairment is crucial for establishing the necessary support.

Developing methodologies to assess user experiences for differently-abled workers is essential for gathering pertinent evidence. Recent work has emphasised the urgent need to critically investigate the impact of assistive technologies on diverse end users with various impairments (Goodley et al. 2020). Exploring the diversity of impairments and challenges faced by individuals with unique needs is crucial, requiring developing systems tailored to these specific requirements.

Finally, research studies should focus on ethical considerations related to the use of Industry 4.0 technologies, covering issues like privacy, consent, and potential biases in technology. Additionally, conducting a comprehensive cost-benefit analysis considering both social and economic aspects of implementing assistive technology would offer valuable insights.

Further research is required to ensure that anthropocentric perspective (Rauch, Linder, and Dallasega 2020) positively impacts workers' well-being. Currently, there is insufficient integration of human factors into I4.0 technology, with limited evidence on how these technologies can be integrated with existing manufacturing systems (Gladysz et al. 2023). Additionally, there is a lack of evidence supporting the idea that I4.0 creates opportunities for more sustainable production, as it is more system/machine-oriented than human-oriented (Mourtzis, Angelopoulos, and Panopoulos 2022). Descriptions in literature portray I4.0 as operating similarly to traditional methods but in a digital way (Beier, Niehoff, and Hoffmann 2021). Furthermore, the concept of O4.0 (Romero et al. 2016) is currently in an early stage of development, with insufficient technological readiness. Therefore, additional research and development are necessary, especially regarding the aspect of economic and social effects.

5.3.2. Technology directions

In their work (Mark, Rauch, and Matt 2021b), outlined potential and forthcoming pathways for assistance systems from I.4.0 tailored to workers in manufacturing. Their aim was to suggest strategies endorsed by stakeholders that maximise the advantages of these systems and enhance their viability in the industry. For instance, developing cognitive systems that integrate digital technologies to enhance maintenance in production, manufacturing execution, and planning operations is essential. Additionally, there is a need for the creation of physical systems like wearable machines, exoskeletons, lightweight cobots, and sensorial aids such as smart sensor networks. The integration of Cyber-Physical Systems, Artificial Intelligence, and the Internet of Things is crucial for optimising manufacturing processes.

Flexible work arrangements facilitated by I4.0 technologies are necessary for balancing health needs and work. This includes providing options for flexible work hours, remote work, or accommodations to support workers facing challenges. Also, improving human-machine interfaces by incorporating ergonomic studies and designs that enhance collaboration between humans and machines is another priority.

Ensuring accessibility to websites, apps, software, and other digital services is vital to supporting individuals with challenges. Designing digital tools and platforms with accessibility as a primary requirement and providing training for employees are key considerations. Addressing communication barriers for some workers can be achieved through the use of assistive technologies or tools to facilitate effective communication.

However, several challenges must be faced; for instance, the I4.0 core technologies require infrastructure, resources, and expertise to integrate these technologies effectively, which are unavailable in every nation. Additionally, the current education system needs adaptation to meet the specialised skills demanded by I4.0, yet only a limited number of individuals have access to quality education and training to fully leverage these opportunities. Consequently, the workforce without reskilling and upskilling processes is exposed to displacement, and traditional jobs could become obsolete.

5.3.3. The I5.0 human-centered perspective

According to (Müller and Commission, E., for Research, D.-G., Innovation 2020), various technologies labelled as I4.0 lack a broader purpose beyond economic benefits. However, technologies facilitating human-machine interaction, like augmented reality, virtual reality, and collaborative robotics, are considered part of the Industry 4.0 concept and are employed globally to assist humans and create value. In summary, some Industry 4.0 concepts are being rejuvenated under new terminology. Industry 5.0, in contrast, focuses on values such as human-centricity, ecological benefits, and social benefits rather than specific technologies. The central idea of Industry 5.0 is to select technologies based on ethical considerations of how they support human values and needs, not solely on their technical or economic achievements.

(Breque et al. 2021) suggests that I4.0 may not be the suitable framework for achieving the SDGs, as it aligns more with the optimisation of business models and economic thinking, potentially leading to technical monopolies and wealth inequality. Consequently, the clarity of the benefits from the integration of I4.0 with the SDGs is uncertain, necessitating more extensive research to align with the new paradigm of I5.0 in their pursuit of sustainability. According to (Mourtzis, Angelopoulos, and Panopoulos 2022), Industry 5.0 (I5.0) positions sustainability and human well-being at its core, representing a new paradigm that facilitates the coexistence of industry with emerging societal trends and needs. As I5.0 offers future opportunities based on human-centricity, sustainability, and resilience, it is emphasised that their potential requires additional research to complement existing Industry 4.0 (I4.0) approaches.

5.3.4. Hedonomics as principles and practices for optimizing well-being for individuals with disabilities

'Hedonomics' is a contraction that combines two terms: 'hedonism' with 'ergonomics', standing for the notion of individual pleasure and product efficiency, respectively. The concept of hedonomics was introduced by (Hancock, Pepe, and Murphy 2005) as a branch of science and design devoted to the promotion of pleasurable human-technology interaction. The advantages of this approach include transforming the unpleasant nature of work into an interesting and engaging activity. Hence, applying ergonomic principles in the design of the work environment, equipment, and tasks can be customised to tailor the special needs of workers with unique abilities, taking into account a more emotional approach to ensure their happiness. For instance, adjustable desk heights, tool positioning, specialised assistive hardware and software, and ergonomic chairs were included by several researchers in customised workstations to meet specific requirements of individuals. Also, flexible work arrangements such as flexible work hours and remote work options to accommodate the workers' preferences and needs can contribute to well-being.

6. Conclusions

This work presented a systematic review of validated technologies that could enhance the inclusion of differently-abled workers in manufacturing. Those studies exposed collaborations between workers and robotic arms to support physical impairments and to decrease workload. Also, cognitive aids using assistive projection systems supported the worker's deficiencies like memorisation, reasoning, or decision-making during different tasks. Besides, to improve the worker's performance, assistive systems were integrated into workstations to monitor the worker's activity and error detection systems to provide feedback. Finally, gamification was presented as another alternative for increasing motivation and engagement. By using these I4.0 technologies, participants with diverse abilities were able to carry out more complex tasks, reduce their mental workload, accelerate production rates, acquire new skills, and execute tasks independently, among other benefits. However, to fully validate the obtained results there's an ongoing requirement for long-term studies, standardised methodologies, and statistical assessments conducted by a representative cross-section of participants.

Enabling individuals with challenging needs to actively participate in manufacturing through I4.0 technologies can bring broader economic benefits, including increased workforce participation, reduced reliance on social support systems, and improved overall societal well-being. In addition, highlighting I4.0 technologies that are conducive to supporting differently-abled workers in manufacturing is crucial for fostering a more inclusive, equitable, and productive industry that capitalises on the strengths and capabilities of all individuals. If these systems enable individuals to participate in work, new employment opportunities can be created.

However, as technology from I4.0 promises unprecedented levels of efficiency, productivity, and innovation, there is an underlying concern about their real benefits for all the communities, as there is unequal access to technology, disparities in workforce skills, job displacement concerns, and exclusion of certain groups from reaping the full benefits of this technological revolution. Thus, it has been suggested that I4.0 may not be the suitable framework for truly achieving inclusivity, and I5.0 is emerging as a new framework focused on technologies based on ethical considerations about human needs, not solely technical or economical achievements.

To address the real-world challenges of individuals with special needs, stakeholders must recognise these challenges and work towards providing equal access to technology, education, training, and sustainable practices. Only then can Industry 4.0 live up to its promise of a revolution that benefits all of humanity, regardless of background or location.

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Authors contribution

M.R., D.C.B., J.M., conceived of the presented idea. M.R., D.C.B., J.M., and D.L-B. carried out the papers screening. P.P. and A.M. contributed to the final version of the manuscript. All authors provided feedback on the research, analysis, and manuscript.

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