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Inclusive Human-Centric Manufacturing – reviewing vulnerable workers' demands

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Abstract. Labor shortages and skill gaps represent risks to economic growth, while at the same time many people remain outside the workforce due to factors such as age or disability. Vulnerable groups, e.g. people with disabilities, elderly workers, and younger workers, may however, have specific workplace demands. Thus, the aim of this study is to give guidance to developers towards creating more inclusive manufacturing systems. This study guides developers toward inclusive manufacturing systems via a structured literature review identifying demands across physical, cognitive, and sensory capabilities, plus accommodation, access, skills, and motivation needs. Findings distinguish demands enabling task performance from those ensuring retention, proposing a strategic roadmap that shifts from assistive technologies to holistic system design for equitable, safe, and efficient workplaces.

1 Introduction

Rapidly changing demographics in Europe and other parts of the world is leading to smaller, as well as older workforces, which negatively affects economic growth[1]. At the same time, over 50 million people in the European Union are not included in the workforce[2]. Major parts of this demographic groups are old and young people, and include people with some kind of reduced ability. The United Nations' sustainability goals include aims for employment and decent work for everyone by 2030, regardless of disability, age or sex[3].

The simultaneous trend of changing skill demands, creates further challenges for competitiveness and financial sustainability[2]. Manufacturing companies need skills related to technological systems, digital and resilient manufacturing, digital human work styles, and the green industrial transformation[4]. Different strategies are used by companies, such as skill development initiatives, up-skilling platforms, strategies for employee engagement, leadership styles and technological innovations[5]. Despite these strategies, challenges still remain in bridging the skill gap.

A wide variety of technologies have the potential to assist operators through physical and cognitive support, such as collaborative robots, pick-by-light systems, and augmented reality

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projectors[6]. Technologies have the potential to create a more inclusive manufacturing industry through augmentation, human-machine symbiosis, and worker empowerment. However, vulnerable groups, such as people with disabilities, elderly workers, novice workers, and low educated people might have certain demands on their workplaces.

While recent reviews have mapped the theoretical intersection of disability and Industry 5.0 [7] there remains a lack of practical, structured guidance for practitioners. The literature identifies that gaps exist, but does not provide a structured implementation framework for factory managers to address them.

Therefore, the aim of this study is to provide developers with guidance towards creating more inclusive technology and workplace designs by identifying existing literature on the demands and needs of vulnerable worker groups in manufacturing. This study aims to answer the following research questions:

What manufacturing workplace demands relevant to vulnerable groups are identified in literature? How does current research propose to meet these demands?

2 Method

A structured literature review was conducted to identify research addressing the inclusion of vulnerable groups and their work-related demands in the context of manufacturing industry. The selection process is visualized in Figure 1.

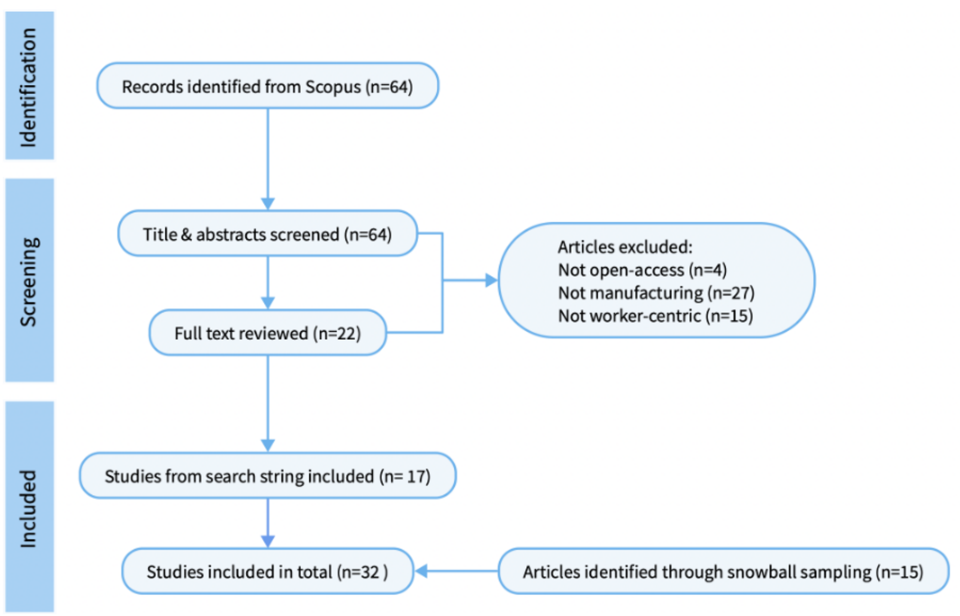

Figure 1: Flow diagram illustrating the review process

The following search string was used in the Scopus database for acquiring an initial list of potential articles:

"(TITLE-ABS-KEY("Industry 5.0" OR "digital technologies" OR "smart manufacturing" OR "human-centric manufacturing" OR "advanced manufacturing")) AND (TITLE-ABS-KEY("need" OR "demand" OR "capability" OR "ergonomics")) AND (TITLE-ABS-KEY("Disab*" OR "Blind" OR "Deaf" OR "vision impaired" OR "hearing impaired" OR "cognitive impairment" OR "elderly workers" OR "aging workforce" OR "low-income workers" OR "Low-skilled workers" OR "vulnerable groups" OR "Neurodiversity")) AND (TITLE-ABS-KEY("workplace" OR "factory" OR "manufacturing" OR "operator" OR "workstation" OR "human-technology interaction")) AND (LIMIT-TO (LANGUAGE,"English")) "

As terminology in this field is continuously evolving, it is acknowledged that some studies may not have been identified through the use of the search string due to variations in how functional abilities and inclusion are described. Snowball sampling was therefore applied to broaden the scope. The initial search resulted in 64 articles. All 64 articles went through title and abstract screening. 22 articles were full-text reviewed, and 17 of those were included the result of this paper. For studies to be included, they had to be in English, open-access, and in the context of the manufacturing industry and be worker-centric, including information or worker characteristics, demands, or enabling technologies and practises.

Worker capabilities and corresponding assistance systems can be categorized into three groups: physical capabilities, sensing capabilities, and cognitive capabilities [8]. Similarly, the demands and needs extracted from this literature review were categorised in the same three categories. Physical capabilities entail energy expenditure driven muskoskeletal movements, such as walking or assembling. Sensing capabilities consist of the functions that allow the operator to collect information from the environment, e.g. though vision or sound, and to filter these sensorial signals. Cognitive capabilities encompass mental tasks such as perception and decision-making. Identified needs and demands belonging to these three categories are presented in the subsection "Core demands", while demands not belonging to these categories were put in the subsection "Other categories identified in the literature review".

2.1 ICF

ICF, the International Classification of Functioning, Disability and Health, is used as a standard framework and language for describing a person's levels of capacity and performance[9]. Disabilities are sometimes classified in a binary way by grouping people into the categories "disabled" or "not disabled". ICF on the other hand focus on the level of functioning, considering that everyone can experience health decline leading to some level of disability, whether it is temporary or continuous. Furthermore, diagnoses are not sufficient for predicting work performance, which is why ICF and its levels of functioning are needed. ICF can be used as a common metric to collect and compare data in situations such as determining individual levels of functioning, assessing needs, evaluating interventions, determining effective use of resources, or making research results comparable[9].

ICF is organized in 4 parts: Body Functions & Body Structures, Environmental Factors, Activities & Participation, and Personal Factors[10]. Body Functions entail both physiological and psychological functions, such as mobility of joints or memory. Body structures, on the other hand, are about the anatomical parts, for example, the trunk or the respiratory system. Activities and Participation include the execution of tasks and involvement in life situations, e.g., walking or basic interpersonal interactions. Environmental Factors are the physical, social, and attitudinal factors in the environment, such as products for communication, colleagues, and societal attitudes. Personal factors are not yet classified in ICF due to the large variation and cultural dependencies, but they entail individual characteristics that influence functioning[11]. Examples of Personal Factors are age, gender, and education.

The paper uses ICF as a structure to understand the different personal profiles and needs of targeted users.

3 Result

3.1 Target groups

Four target groups can be seen in the literature reviewed: elderly workers [12], younger workers [13], workers with disabilities [14], and workers in general [15]. These groups are often presented separately, without acknowledging that the groups can overlap [16].

A contrast can be found between literature focusing on workers with disabilities and literature addressing workers in general. Demands regarding people with disabilities highlight the importance of individual adaptation of workplaces based on each person's needs [17, 18, 19], while the demands for workers in general are based on e.g. standardized methods for ergonomic assessments [15, 20].

The literature review indicated a difference in skill gaps between elderly and novice professionals. Elderly workers lack skills connected to technological advancements [21], but novice professionals require industry-specific skills [13]. Flexible study methods, such as online training, were described as more suitable for novice professionals [22], while it was reported that elderly workers need continuous training [21] and addressing recistance to new technology [23]. Both novice and elderly workers wanted practical live training and lessons [13] [24].

3.1.1 Elderly workers The limitations of the aging workforce are described in the literature in the context of both disabilities and skills. [25] mention the Body Functions "Neuromusculoskeletal and movement related functions" and "Sensory functions and pain". Through the Nordic Musculoskeletal Questionnaire, it was revealed that increasing age is somewhat associated with an increase in pain, fatigue, and discomfort in relation to performing work tasks. Specifically, musculoskeletal symptoms were reported in the spinal column and upper limbs. The paper, however, did not include what demands this creates for a workplace, or what enablers could help in this matter. [12] also reports on Body Function-based limitations, revealed through a motion analysis of elderly workers, younger workers, and younger workers with emulated abilities of elderly workers. A decrease in muscle strength and visual range was the main reason for lower work task performance. This falls under the ICF categories "Seeing functions" and "Muscle power functions". [12] explains that elderly workers require workplaces with fewer complex motions, since they typically perform one motion at a time, instead of conducting simultaneous movements like younger workers. Furthermore, elderly workers showed a higher hand idling time, meaning that their hands are inactive for a longer time while conducting a task.

[21] conducted a survey with HR managers. Most of the companies that replied to the survey did either not notice a decline in psycho-physical abilities among elderly workers or stated that it is mitigated. Only one company thought that the production was affected by it. The paper does, however, not explain further what psycho-physical decline specifically entails. Environmental Factors are also mentioned in the paper, such as interpersonal relationships, stress, workload, and work environment in general. The survey showed that Personal Factors, such as skills and resistance to change, had an importance. 42% of the survey respondents stated that there is a risk of certain skills becoming outdated due to rapid technological advancements. Therefore, elderly workers need continuous training. This can be done through, for example, job rotation and job enlargement. [23] also state skill gaps and resistance to new technologies as a limitation among elderly workers. Through a questionnaire, it was found that there is a need for

continuous learning while valuing the workers' long experience, which, according to [23], can be achieved through knowledge-oriented leadership. [24] let elderly people conducted a task with a collaborative robot and concluded that their lower experience of tablet GUIs was the reason for conducting the tasks more slowly. Training is needed to accept new technology, especially through direct interaction.

3.1.2 Novice Workers For novice professionals, Personal Factors are mentioned as limitations, namely their skills, or lack thereof, as seen in [13] and [22]. [22] reports skill gaps in fields such as digital systems, automation, robotics, measurement, and general machining. Flexible study methods such as online learning are most suitable, but there is some resistance in using technologies such as VR and AR for upskilling. [13] evaluated novice professionals' use of MOOC platforms and identified factors of importance for the target group. The course participants emphasized the importance of sufficient content depth and contextualization, as well as industry-specific training. They also wished for direct contact with experts through for example, through visits and practical lectures.

3.1.3 Workers with disabilities [26, 26, 27, 28] focus on the category Body Functions, with [29] and [26] including the terms "physical" and "mental" disabilities, while [27] and [28] specify "mental disabilities" and "cognitive disabilities", that is, the ICF subcategory Mental Functions. The characteristics of the disabilities are not further defined in the literature. [28] state that projected in-situ instructions are beneficial for workers with cognitive disabilities, as they require continuous assistance. [29] simulated an assembly system, including workers with mental disabilities, under the assumption that they would need increased time for conducting work tasks. The study concluded that parallel flows are more beneficial than conventional line flows when including disabled workers. [30] also simulated the impact of having disabled workers in production. Simulations can be used for integrating disabled workers into the production, and for coordinating work with the other employees. The data used in the simulations were collected as part of a case study. The authors state that variations in individuals with the same disability group may be large, and therefore, forms of instruction should be chosen on an individual basis.

[26] proposed a system that matches the in-situ capabilities of a worker with the process requirements. They state the need for customized workplaces based on the individual needs of the worker. In their system, they include factors such as motor function, body motion, perception, cognitive capabilities, ergonomics, and complex capabilities. However, the dependencies of these factors need to be modelled to increase the quality of the capability matching. [27] and [16] conducted literature reviews on assistance systems for production workers with mental and physical disabilities. The assistance systems are presented in three categories: sensing, physical, and cognitive aid systems. [16] states the need for a deep understanding of individual physical and cognitive capabilities and their impact on work tasks. [16] also highlights the importance of taking into consideration individuals with multiple disabilities, as well as a group of workers with different disabilities. No accommodation for a specific disability should come at the expense of another.

[31] conducted interviews in 2 companies employing people with disabilities. The authors concluded that improving the work environment for people with disabilities requires treating them equally as other workers and enabling them to express their individuality at work. This entails meeting individual needs, such as providing redesigned tools, offering devices, or having adjustable equipment to enable the worker to conduct the same tasks as the other workers. Furthermore, workers should be supported in the type of work they want to do, transferring them to different stations, to optimally use the capabilities of each worker.

3.1.4 Workers in general [32, 33, 15, 20] present technological enablers for improving the working conditions for workers in general. [32] developed a methodology for assessing the suitability of conducting tasks with collaborative robots. Assessment metrics such as physical ergonomics, cognitive ergonomics, and health and safety are used. [33] proposed a methodology for assigning picking tasks to workers based on the energy expenditure required and the individual workers' capacity. The workers' allowable energy expenditure rate (WAEER) can be calculated using variables such as age, sex, body weight, and lifestyle. With the WAEER, workloads can be adjusted to each worker. [15] presents a motion-capture system for ergonomic risk assessments based on the Rapid Entire Body Assessment (REBA) and Rapid Upper Limb Assessment (RULA). [20] also proposed a digital assessment system, but based on the European Assembly Workseet (EAWS), considering factors such as musculoskeletal, muscular, and handling risks. The system gets its data from motion capture cameras, RFID-based smart gloves, and surface electromyography.

3.2 Core demands

The literature review revealed that categorizing assistive technologies can be divided in three categories, namely physical, cognitive, and sensing, as done by [8, 16]. Similarly, a simplified grouping of worker capabilities and demands can be done with the same three categories. These demand types are commonly addressed by technological and organizational solutions, and represent core biological demands that need to be considered for workers to conduct tasks in a safe and efficient manner, e.g. related to physical and cognitive ergonomics [32].

3.2.1 Physical Limitations and demands related to physical capabilities were identified [32, 12, 14, 34, 16]. Universal worker constraints can be identified in ergonomic assessment methods, such as Rapid Entire Body Assessment (REBA), Rapid Upper Limb Assessment (RULA)[15], and the European Assembly Worksheet (EAWS)[20], which is used to assess musculoskeletal, muscular, and handling risks. Information on human factors such as ergonomics can be used as a base for job-rotation models [35], as well as for task allocation between humans and robots [26, 36, 33].

Energy expenditure was also found to be a constraint [36, 33]. Operator specific energy expenditure rate can be quantified using factors such as age, sex, body weight, and lifestyle [33]. By knowing how many kcal per minute a worker can spend, in relation to the energy expenditure rate required, tasks can be assigned in a way that minimizes fatigue.

Vulnerable workers may have additional needs. Elderly workers may experience physical changes in e.g. strength, endurance and flexibility [37]. The tendency for pain, discomfort and fatigue, increase slightly with age[25]. It has also been observed that older workers have longer idling time, while younger workers conduct multiple motions at one, meaning that work tasks with fewer complex motions are more suitable for elderly people[12]. These findings were validated by emulating physical constraints of elderly workers through the use of knee and elbow restraints limiting joint mobility, as well as weights built into anklets, bracelets and a vest.

Workers with disabilities require physical support to overcome impairments and reduce workload [34]. Study participants with disabilities reported having limitations related to e.g., neuromusculoskeletal and movement-related functions connected to the head, functions of the respiratory system, hand and arm use, and walking, which need to be taken into consideration for successful integration into cobot workstations (35). If a worker has limitations to movement-related functions, the workstations need to be designed in a way that allows the worker to move between them [38]. In the case of limited fine hand movements, projected assembly instructions should have an appropriate spacing [18]. Furthermore, it has been reported that workers with disabilities may need up to 20% additional time for rest compared to other workers [39].

3.2.2 Cognitive Cognitive ergonomics demands need to be addressed to optimize mental workload [32, 34, 16]. Operators cognitive and perceptual capacities can be monitored to match with process requirements [26]. Elderly workers may have functional limitations related to cognitive functions such as slower problem-solving or reaction times [37].

People with disabilities related to mental functions might need continuous guidance in picking and assembly operations [38], potentially with two-way communication [40] and feedback systems [19]. The order and number of simultaneous instructions should be in proportion to the worker's skill level and the complexity of the task [18], as well as the complexity of the description itself [19]. Visual instructions showed best performance among workers with disabilities related to mental functions, while audio and tactile feedback was considered disturbing [28]. People with disabilities related to memory functions, calculation functions, problem solving, articulation functions, mental functions of language, orientation functions, reading, visual perception, and higher level cognitive functions, performed better when multiple instructions were shown simultaneously when using a projection system, which enables the workers to pick multiple parts at the same time[18]. When instructions are shown one at the time, the worker gets limited by the system response speed. People with disabilities related to mental functions, visual acuity functions, reading, and other body functions, can benefit from systems that automatically detect when operators don't know how to initiate interaction, as well as an increase in number of grammar rules for speech based interactions[40].

3.2.3 Sensing Workers may have different sensing capabilities that will affect the appropriate mode of instructions [38, 19, 16]. For example, task descriptions can be given by visual and audio cues, but if the worker has a limitation to hearing functions, stroboscopic lights can be used to indicate what parts to pick. If the disability instead consists of limitations of seeing functions, verbal cues, consisting of one or two words, can be used for guidance. Audio instructions could be complemented by real-time captions [19] and color schemes customized to people with limited visual acuity [18]. Elderly people may experience deterioration in sensing functions such as hearing or vision [37].

3.3 Other relevant categories identified in the literature review

3.3.1 Capability accommodation A systematic review of assistive systems for operators with disabilities revealed that research often focus on one disability when evaluating work tasks, without taking into account that an individual may have a combination of multiple disabilities[16]. Different operators in the same workplace may also have different disabilities, and when research focus on only one type, it can come at the expense of another type.

However, several studies examine adaptive, personalized and customizible systems [26, 17, 38]. Personal characteristics are influential factors of system performance, and therefore needs to be addressed [39, 41]. Physical assistive technologies must be customized to fit the user [42]. The same applies to sensing limitations; for example, if an operator has a limitation related to hearing functions, stroboscopic lights can be used to indicate what parts to pick, but if the functional limitation instead is related to seeing functions, verbal cues can be used for guidance [38]. Visual and audio instruction systems can be complemented with personalized stimulus when a task has been completed, e.g. in forms of videos, food, music, or audio messages.

Projection systems can be adapted to visual preferences, such as color customization for people with limited visual acuity, spacing for people with limited fine hand use, and order and number of instructions based on worker skill level and task complexity[18]. Audio instructions can be complemented by real-time captions [40], and the complexity of textual descriptions can also be adapted[19].

There is a need for human-robot collaboration to adapt to individual needs, for example through a system that analyzes the operator's capabilities in real-time and automatically allocates tasks between the operator and a robot [26]. Such factors can entail ergonomics [26, 35] or energy expenditure [36, 33]. The operator capabilities can also be evaluated for the entire process instead of per task [36].

Multiple modes of operations should be offered, e.g. both automatic and manual options, to find the right level of assistance [17]. Multiple stop options and automatic reaction to problems are also required, due to operators differences in body functions.

3.3.2 Skill Because of the aging workforce and declining birth rates, there is a need of transferring knowledge from older experts to newer workers[22]. The skill demands are for example connected to digital systems, automation and robotics, measurement skills, and general machining skills. Companies sees flexible and self-directed methods as most suitable, e.g. online learning, and are hesitant towards AR and VR for skill development[22].

Younger people evaluating a MOOC (Massive Open Online Course) platform, stated that factors of importance include content depth, contextualization, content review, industry specific training, direct contact with experts, and video quality[13]. Elderly workers, in contrast, need continuous training to address the changing skill requirement driven by technological advancements[21]. Strategies such as task reassignment, job rotation, and job enlargement support knowledge transfer and skill development. However, the need for up-skilling is also accompanied by a resistance to new technologies[23]. Knowledge oriented leadership can be used to find a balance between encouraging learning and at the same time value the workers long experience. In a study involving cobots, elderly workers were slower than other workers, potentially due to their lack of experience with the user interface[24]. However, the workers expressed positive attitudes towards the technology when they got the opportunity to familiarize with the technology through direct interaction.

Workers should be given the opportunity to demonstrate their abilities as individuals, which will let the workers expand their capabilities and help the company avoid skill related bottlenecks [31]. Another strategy for enhancing skill development is through skill-based ranking systems, combined with education opportunities and tests.

3.3.3 Access & participation For cobots to be accepted among workers, fear have to be addressed, as well as social factors [17]. Cobots should be accessible to people with different abilities, so no-one feels left out, and at the same time make sure that the cobot work stationsdon't make workers feel isolated from other people[17].

Prejudices leading to limitation of workers potential has to be avoided[31]. Regardless of disabilities, workers should be treated as equals and be given opportunities to demonstrate their abilities as individuals. The use of each individuals abilities should be optimized by letting the workers choose what type of job they want to do, as well as to give opportunities to task reassignment and job rotations.

A support system for matching people with disabilities with suitable workplaces has been developed [14]. A classification system for disabilities was used to create a data base of workers with disabilities that was compared to a data base with workplaces. Instead of using ICF to classify the disabilities, since it was deemed too broad, a new classification system was developed that better suits the case company. It consists of working hours, type of work, lifting restrictions, mobility restrictions, and other restrictions. The same categories are used to evaluate the workplace, and to specify which restrictions are acceptable. The two data bases are then compared with the help of a program code[14].

Production systems must plan for high individual variability in task completion time, even among workers with the same type of disability [30]. This variability required structured analysis to determine the economic justification of including people in production environments, considering factors such as different levels of financial and non-financial support given, e.g. government subsidies or assistive tools. Other simulation models can instead be used to evaluate error probabilities in human-robot interaction [43], or to evaluate the inclusion of disabled workers in different production system configurations [29], with simulations confirming parallel line flows as more suitable in comparison to line flows.

3.3.4 Motivation Multiple studies address motivation and boredom as factors to optimize productivity and the inclusion of people with disabilities [35, 17, 28, 38]. Information on human factors, including boredom, can be used as a base for job rotation models [35]. Boredom can also be avoided by offering different levels of assistance, as automatic options that might benefit one worker, might make the work too boring for another [17]. Even though a system might be enjoyable to use, an increased difficulty level was preferred, even in cases where additional assistance was needed during learning phases of the system [28]. Motivation can be further enhanced by for example gamified elements [34] with reward systems and progress screens [19], or personalized stimulus such as videos, food, music or audio messages [38].

4 Discussion

Recent work by [7] provided a systematic review of smart workstations, highlighting the disconnect between engineering and social sustainability. Our study builds upon this by operationalizing these findings.

Based on the identified demands, we propose a four-stage roadmap for practitioners to transition toward inclusive Industry 5.0 manufacturing:

- Phase 1: Capability Assessment & Digital Profiling. Before technology adoption, companies must map existing worker capabilities (Physical, Cognitive, Sensorial) against task requirements.
- Phase 2: Targeted Technology Matching. Select adaptable technologies rather than static ones.
- Phase 3: Organizational Adaptation. Technology alone is insufficient. This phase involves implementing flexible job rotation, knowledge-oriented leadership, and skill-ranking systems to support the new technical setup.
- Phase 4: Continuous Evaluation Loop. Use sensor data and feedback to monitor mental workload and fatigue, allowing the system to dynamically re-allocate tasks.

An overview of the roadmapping can be seen in Table 1 based on the sorted papers and corresponding assistive technologies and enablers. Each column represents a thematic category identified in the literature review. For each theme, the table presents the worker demands that the reviewed studies aimed to address, as well as the worker demands that were identified through the studies, for example through direct interactions with users or other stakeholders. The last row of the table summarizes the target groups discussed in the literature, but presented in

ICF terms to enable a standardized and comparable description of functions and abilities across studies. This row illustrates both the link between worker limitations and their demands, as well as the literature's interpretation of how approaches for inclusivity relate to worker limitations.

Table 1: Roadmapping of sorted assistive technologies based on the workplace demands and associated functional limitations, organized by thematic area

	Cobots	**Pick-by-x & projection systems**	**Assessment & Planning**	**Skill development**	**Other**
Demands addressed in studies	· Physical ergonomics · Cognitive ergonomics · Health and safety · Minimize mental workload · Minimize energy expenditure · Adaptable to individual needs · Adaptable to real-time capabilities	· Continuous guidance · Visual cues · Audio cues · Physical support · Personalized stimulus · Verbal interaction · Feedback · Progress tracking · Color customization · Spacing customization · Adaptable complexity of instructions · Real-time captions · Adaptable complexity of language	· Ergonomics · Minimize fatigue · Boredom · Adaptable to real-time capabilities · Working hours · Lifting restrictions · Mobility restrictions	· Educational opportunities · Freedom of choice · Continuous training · Encouragement · Value experience · Familiarization with technology · Direct interaction with technology	· Individual workplace adaptation · Sound graphing · Lower dexterity requirement · Adjustable table height
Demands identified empirically	· Adaptable to individual abilities · Manual & automatic options · Avoid boredom · Multiple stop options · Automatic reaction to problems · Acceptance by workers · Address fear · Social inclusion	· Visual instructions · Instructions for multiple steps simultaneously · Challenging tasks · Additional directions during learning phase · Projected instructions only during learning phase · Detect when users don't know how to initiate interaction · Increased number of grammar rules	· Fewer complex motions	· Avoid prejudices · Treated as equals · Demonstrate abilities as individuals · Flexible · Self-directed · Content depth · Contextualization · Content review · Industry specific · Direct contact with experts · Video quality	· No special treatment of people with disabilities · Opportunity to demonstrate abilities as individuals · Understanding of physical and cognitive abilities · Accommodate multiple disabilities · Work closely with other operators
Targeted functional limitations (Translated to ICF categories)	· Body functions · Neuromusculoskeletal and movement-related functions · Functions of the respiratory system · Hand and arm use · Walking · Learning and applying knowledge	· Body functions · Mental Functions · Personal factors - skills · Memory functions · Calculation functions · Problem solving · Articulation functions · Mental functions of language · Orientation functions · Reading · Visual perception · Higher-level cognitive functions · Fine hand use · Visual acuity functions · Seeing functions · Hearing functions · Movement functions	· Body functions · Neuromusculoskeletal and movement-related functions · Perceptual functions · Mental functions · General metabolic functions · Personal factors - Boredom - Age · Seeing functions · Mobility of joint functions · Muscle power functions · Sensory functions and pain	· Body functions · Personal factors - skills - Age	· Body functions · Personal factors - Skills · Products and technology for employment

4.1 Cobots

Collaborative robots (cobots) are a promising solution to aid workers with disabilities [27, 17]. Cobots should optimize physical ergonomics, cognitive ergonomics, health and safety, and operational efficiency[32]. This can be done by integrating cobots with task allocation systems that focuses on minimizing mental workload, energy expenditure, and makespan for productivity[36]. However people with disabilities can have additional demands, potentially consisting of a combination of multiple disabilities, which requires the human-robot collaboration to adapt to individual needs[26].This could potentially be done through a system that analyzes the operators' capabilities in real-time and automatically allocates tasks between the operator and the robot.

People with limitations related to neuromusculoskeletal and movement related functions connected to the head, functions of the respiratory system, hand and arm use, walking, as well as learning and applying knowledge, expressed a need that cobots should be adaptable to individual abilities[17]. Multiple modes of operations should be offered, e.g. both automatic and manual options, as assistance that might help one worker, might make the work too boring for another. Multiple stop options and automatic reaction to problems are also required, due to operators differences in body functions. For cobots to be accepted among workers, fear have to be addressed, as well as social factors. Cobots should be accessible to people with different abilities, so no-one feels left out, and at the same time make sure that the cobot work stations don't make workers feel isolated from other people[17].

4.2 Pick-by-x & Projection systems

Picking and assembly operations guided by visual and audio cues can be used to guide people with disabilities related to mental functions[38]. If the worker also has a limitation related to hearing functions, stroboscopic lights can be used to indicate what parts to pick. If the mental disability instead is combined with limitations of seeing functions, verbal cues, consisting of one or two words, can be used for guidance. However, if the worker also has limitations related to movement functions, the work stations need to be designed in a way that allows the worker to support themselves moving between them. The visual and audio system can be complimented with personalized stimulus when a task has been completed, e.g. in forms of videos, food, music, or audio messages.

Projection based systems can also guide operators by projecting instructions directly onto the workstation[27, 28, 18, 40, 19]. The projection system can be combined with verbal interaction [40] and feedback [19]. Gamified elements can also be included, such as reward systems and progress screens[19]. The projection systems can be adapted to visual preferences, such as color customization for people with limited visual acuity, spacing for people with limited fine hand use, and order and number of instructions based on worker skill level and task complexity[18]. Audio instructions can be complemented by real-time captions [40], and the complexity of textual descriptions can also be adapted[19].

Visual instructions showed best performance among workers with disabilities related to mental functions, while audio and tactile feedback was considered disturbing[28]. People with disabilities related to memory functions, calculation functions, problem solving, articulation functions, mental functions of language, orientation functions, reading, visual perception, and higher level cognitive functions, performed better when multiple instructions were shown simultaneously, which enables the workers to pick multiple parts at the same time[18]. When instructions are showed one at the time, the worker gets limited by the system response speed. The study participant expressed that although the system is enjoyable to use, an increased difficulty level for the tasks would be preferred. However, most of the study participant needed additional support in using the projection system during the learning phase of using the system. Novice workers can also benefit from projected instructions to learn assembly tasks, but once learned, the projections can become distracting[28]. People with disabilities related to mental functions, visual acuity functions, reading, and other body functions, can benefit from systems that automatically detect when operators don't know how to initiate interaction, as well as an increase in number of grammar rules for speech based interactions[40].

4.3 Assessments & Planning

A variety of assessment methods can be used to evaluate ergonomics, worker capabilities, and task performance, which can be used as a basis for planning workplaces and allocating tasks.

Motion capture systems can be used to assess ergonomic risks, based on e.g. Rapid Entire Body Assessment (REBA), Rapid Upper Limb Assessment (RULA)[15], or the European Assembly Worksheet (EAWS)[20], to assess musculoskeletal, muscular, and handling risks. The tendency for pain, discomfort and fatigue, increase slightly with age[25]. It has also been observed that older workers have longer idling time, while younger workers conduct multiple motions at one, meaning that work tasks with fewer complex motions are more suitable for elderly people[12]. An "elderly experience teaching suit" can be used to emulate these characteristics of elderly workers. The suit consists of goggles that restrict visual range, elbow and knee restraints, and weights built into a vest, bracelets, and anklets. This way, younger people could experience the functional restrictions of older people.

Information on human factors, such as ergonomics and boredom, can be used as a base for job rotation models to optimize the productivity[35]. It can also be used for task allocation between humans and robots [26, 36, 33]. Real-time information on the operators capabilities can be collected, such as ergonomics, motor functions, perception, cognitive, and body motion, to match with process requirements[26]. The operator capabilities can instead also be evaluated for the entire process instead of per task[36]. Energy expenditure can also be a variable in task allocation[36, 33]. The operator specific working energy expenditure rate (WAEER) can be quantified using factors such as age, sex, body weight, and lifestyle[33]. By knowing how many kcal per minute a worker can spend, in relation to the energy expenditure rate required, tasks can be assigned in a way that minimizes fatigue. A simulation using WAEER for task allocation showed that older workers aren't necessarily a limitation in the workforce, because other individual and task specific factors have an impact as well[33].

A support system for matching people with disabilities with suitable workplaces has been developed[14]. A classification system for disabilities was used to create a data base of workers with disabilities that was compared to a data base with workplaces. Instead of using ICF to classify the disabilities, since it was deemed too broad, a new classification system was developed that better suits the case company. It consists of working hours, type of work, lifting restrictions, mobility restrictions, and other restrictions. The same categories are used to evaluate the workplace, and to specify which restrictions are acceptable. The two data bases are then compared with the help of a program code[14].

Task completion time may vary greatly between operators even if they have the same type of disability[30]. This data was used to plan the involvement of workers with disabilities in the production, through a method based on system dynamics and discrete event simulation. The purpose of this simulation model was to determine if it is economically justified to include people with disabilities in the production, considering factors such as different levels of financial and non-financial support given, e.g. government subsidies or assistive tools[30]. Other simulation models can instead be used to evaluate error probabilities in human-robot interaction, considering psycho-social, mental, behavioral, and physical factors[43], or to evaluate the inclusion of disabled workers in different production system configurations[29]. The simulation of production configurations revealed a higher suitability for parallel line flows when workers with disabilities are included, in comparison to line flows. The analysis was based on assumptions such as longer assembly time and tasks only partially conducted by workers with disabilities.

4.4 Skill Development Methods

Because of the aging workforce and declining birth rates, there is a need of transferring knowledge from older experts to newer workers[22]. The skill demands are for example connected to digital systems, automation and robotics, measurement skills, and general machining skills. Companies sees flexible and self-directed methods as most suitable, e.g. online learning, and are hesitant towards AR and VR for skill development[22].

Younger people evaluating a MOOC (Massive Open Online Course) platform, stated that factors of importance include content depth, contextualization, content review, industry specific training, direct contact with experts, and video quality[13]. Elderly workers, in contrast, need continuous training to address the changing skill requirement driven by technological advancements[21]. Strategies such as task reassignment, job rotation, and job enlargement support knowledge transfer and skill development. However, the need for up-skilling is also accompanied by a resistance to new technologies[23]. Knowledge oriented leadership can be used to find a balance between encouraging learning and at the same time value the workers long experience. In a study involving cobots, elderly workers were slower than other workers, potentially due to their lack of experience with the user interface[24]. However, the workers expressed positive attitudes towards the technology when they got the opportunity to familiarize with the technology through direct interaction.

Prejudices leading to limitation of workers potential has to be avoided[31]. Regardless of disabilities, workers should be treated as equals and be given opportunities to demonstrate their abilities as individuals, which will let the workers expand their capabilities and help the company avoid skill related bottlenecks. The use of each individuals abilities should be optimized by letting the workers choose what type of job they want to do, as well as to give opportunities to task reassignment and job rotations. One strategy for enhancing skill development is through skill based ranking systems, combined with education opportunities and tests[31].

Worker's differences affect factors such as productivity, cost and time[44]. Skill and fatigue are mentioned in research as reasons, while age, gender and disability is not commonly considered. There are however multiple cases were products and technologies commonly used hinder employment, and therefore other tools and devices have been introduced to aid workers specifically with their particular disability[31]. For example, workers with limited hearing functions can use a sound graphing device for sound inspections, or workers with limitations related to fine hand use, can use a redesigned tool that lowers the requirement for the use of fingers in part handling. Other adaptations of the work environment can entail adjustable table heights, which aids wheelchair users.

A systematic review of assistive systems for operators with disabilities, revealed that research often focus on one disability when evaluating work tasks, without taking into account that an individual may have a combination of multiple disabilities[16]. Different operators in the same workplace may also have different disabilities, and when research focus on only one type, it can come at the expense of another type.

4.5 Demands

Several studies describe the differences in human capabilities, and the need for addressing them. [16] however highlights that human capabilities, and the combination and levels of them, are very individual, while some assistive solutions are specifically designed only for a specific disability, as reported by [31]. Furthermore, studies categorizing technological solutions by the three core capability types, address how the technology supports worker capabilities, but this review also includes what demands the worker has on the technologies themselves.

The findings also indicate demands beyond biological capabilities. There is a need for universal design with individual capability accommodation, meaning that technological enablers should be able to be used by everyone and benefit everyone. The literature review shows that there is a need for solutions that can be used by people with different disabilities [17, 18, 19]. One of the reasons is that it is not uncommon for people to have a combination of multiple disabilities, but it is also needed from a social perspective, since workers don't want to feel left out [17]. Furthermore, although not discussed in the papers from the literature review, the implementation costs of new technology or tool redesign can be high, which makes it important that the implemented solutions can be both used by and beneficial to multiple people.

For assistive technologies to be effective, they have to be accepted by the workers as well. Fear and social aspects [17] have to be taken into consideration, including motivation [38, 17, 19]. The right balance between assistance and challenge must be found to keep the workers engaged.

The findings also show that there are factors that need to be addressed for vulnerable workers to even access opportunities for participation, such as related to adaptable and customizable systems [38, 17], skill development opportunities [31], and workplace matching [14]. The core demands that are connected to performing tasks, are intertwined with the demands that are connected to getting the work opportunities in the first place, since both are required for inclusive manufacturing

4.6 Limitations
As this study aims to give an initial indication workplace demands of diverse worker groups and to create an understanding of the research gap, there are some limitations that have to be considered. The search string included terms that may not completely align with current terminology used in research, as inclusive terminology is continuously evolving. This choice was made to capture a broad range of studies, but may at the same time have limited the inclusion of relevant articles. The number of sources included in this literature review is not sufficient to create a complete picture of the many technologies existing and their demands from all combinations of worker limitations. Furthermore, no evaluation has been conducted on the effectiveness of the proposed enablers found in the literature review.

4.7 Future research
Future research should address the limitations of this study, and review a larger number of sources to create a more detailed mapping of demands and methods to address them. This should begin with redefining the search strategy and terminology used to capture a broader range of studies. In addition, the effectiveness of the technological enablers should also be taken into consideration.

There is also a need of collecting empirical data on diverse workers demands through direct interaction with the people in question, as a large portion of past research have based on assumptions or with other stakeholders. Future studies should also further investigate and develop adjustable and customizable solutions that can assist workers with diverse abilities and skill levels, as well as assess social factors, such as acceptance, social inclusion, and motivation. Future research should also validate the proposed roadmap through longitudinal case studies in pilot factories.

Finaly, it should also be explored how the International Classification of Disability, Functioning, and Health (ICF) can be further integrated in research on worker diversity in the manufacturing industry. Worker limitations are commonly vaguely described in manufacturing research, and could benefit from a common language to facilitate comparisons across studies.

5 Conclusion
This study synthesized the demands of vulnerable worker groups in the manufacturing industry. We identified that while Core Demands (physical, cognitive, sensing) determine the immediate feasibility of work, Contextual Demands (leadership, training, social inclusion) determine the long-term sustainability of the inclusion. To support the manufacturing industry's transition, we

presented a strategic roadmap. This roadmap shifts the focus from purely 'assistive technology' to a holistic 'inclusive system design.'

The findings from this study contribute towards the creation of guidelines for developers to create inclusive manufacturing environments, where vulnerable workers get the same opportunity to conduct work tasks safely, efficiently, and equitably.

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