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Augmented Workforce: contextual, cross-hierarchical enquiries on human-technology integration in industry

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ABSTRACT

Although shop floors become more automated, manual labor is more than the sum of recurring tasks which can simply be executed by autonomous machines. Where total automation is ineffective, operator assistance systems (OAS) could increase productivity and empower the workforce. Operator Assistance Systems (OAS) are systems that interact with operators to modify their cognitive or physical capabilities whilst performing industrial tasks. Given the important role of humans in future manufacturing environments that cannot be automated, production organizations in industry and Human-Technology Integration (HTI) researchers need to understand where OAS can be deployed and what human factors and other human implications arise from their deployment. In short, capturing views from stakeholders who are both affected by and affect the successful implementation of new technologies are essential to align technological innovations with a human-centric perspective. However, based on our literature review of OAS, we find that there are few technology-neutral enquiries on the industrial applicability of OAS. In particular, we note a lack of considerations of the different requirements for OAS resulting from diverse stakeholders in industry, which is expected to be of importance when designing effective HTI. To address this gap, we explore the industrial context of OAS and the perspectives of stakeholder groups across organizations on the applicability of OAS using a multi-method research approach encompassing 27 qualitative expert interviews and ethnographic observations of three industrial contexts. A key finding of our contextual enquiry is that participants expect OAS to be beneficial on shop floors if designed to improve cognitive abilities, such as inductive reasoning. Further, in the case a company seeks to introduce an OAS to augment physical capabilities of operators whilst attached to their bodies, the data indicate a cautious approach is sensible as many operators reject such a form of augmentation. We highlight what our findings mean for HTI research, especially as it relates to consideration of the highly contextual user requirements when developing and integrating human-technology systems for industry.

1. Introduction

In the 1980's, the car manufacturer GM faced increased competition from global competitors such as Toyota. Striving to retain their competitive edge, executives elaborated a 'lights-out' automation strategy (Ingrassia & White, 1995). The plan was to develop factories that are fully automated and operated by robots-only to enable more efficient production than anyone else. Yet, the company struggled to receive a return on their investment in total automation technology: "as the assembly line tried to gain speed, the computer-guided dolly wandered off course. The spray-painting robots began spraying each other" (Ingrassia & White, 1995). 40 years later, the car manufacturer Tesla picked up the vision of lights-out factories. Again, excessive automation did not produce the desired results and slowed down the company's productivity: "we had this crazy, complex network of conveyor belts […] and it was not working, so we got rid of that whole thing" (CBSInteractive, 2018).

As these examples illustrate, full automation in industry is anything but straightforward, particularly when industrial work is more than the sum of repetitive sub-tasks to be completely automated by autonomous machines (Pfeiffer, 2016). This makes a human workforce likely to remain essential on future shop floors (Longo, Nicoletti, & Padovano,

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2017) and in industrial learning environments (Pacaux-Lemoine, Trentesaux, Rey, & Millot, 2017) for the foreseeable future. This, in turn, makes it necessary to engage end-users and understand the industrial context into which technology is embedded. Consequently, understanding the end-user context of HTI is a key consideration of how technology can allow the workforce to thrive in an production ecosystem (Kaasinen et al., 2020; Moencks et al., 2020).

Advances in HTI and OAS are increasingly blurring the boundaries between humans and artificial agents in industrial systems (Autor, Mindell, & Reynolds, 2020). OAS are systems that interact with operators to modify their cognitive or physical abilities whilst performing a certain range of industrial tasks (cf. Section 2.2). Examples for OAS include: virtual reality glasses (Liu et al., 2018), augmented reality projectors (Uva et al., 2018), wearable technology (Merkel, Berger, Braunreuther, & Reinhart, 2019), connected worker platforms (Zolotová, Papcun, Kajáti, Miškuf, & Mocnej, 2020), context aware applications (Roth, Möncks, Bohné, & Pumplun, 2020), or exoskeletons (Salvadore, Rota, Corsi, & Colombina, 2020). The integration of OAS into industry is an integral part of realizing the concept of the Operator 4.0 or the Logistic Operator 4.0 (Romero, Stahre, & Taisch, 2020; Cimini, Lagorio, Romero, Cavalieri, & Stahre, 2020; Pacaux-Lemoine et al., 2017). Previous work often emphasizes that, while technological aspects are of importance, organizational and contextual issues are highly relevant for many industries as well (Masood & Egger, 2019). However, this has not been reflected to the same extent in the literature (Moencks, Roth, Bohné, Romero, & Stahre, 2021; Moencks et al., 2020).

To realize human-centric production and technology-augmented work, industry and HTI research need to understand the industrial context in which OAS can be applied as well as the highly contextual stakeholder requirements for OAS (Gorecky, Schmitt, Loskyll, & Zühlke, 2014; Siepmann & Graef, 2016; Moencks et al., 2020). However, our literature review on OAS reveals that there are few solution-neutral enquiries on exploring the industrial applicability of OAS. Often, the exploration of OAS is linked with evaluating a specific technological pilot (Kaasinen et al., 2020). Further, the different requirements for OAS resulting from diverse stakeholders, such as operators, technicians and management within the industry, are rarely considered (Moencks et al., 2020). However, stakeholder alignment as an organizational factor is an essential enabler of successful OAS integration projects (Masood & Egger, 2019) and there is currently a gap in exploring how stakeholder groups' perspectives on OAS align. Therefore the central objective of this paper is to conduct a solution-neutral contextual enquiry on cross-hierarchical stakeholder perspectives on OAS' applicability in industry. This gives rise to three research questions:

1. How do cross-hierarchical stakeholders characterize the role of the human operator and technological artefacts on future shop floors?
2. In which contexts of daily business and industrial education would stakeholders be open to leverage OAS?
3. How do cross-hierarchical stakeholder perspectives on OAS applicability align, and how can this alignment influence future technology deployment projects?

To ensure a solution-neutral approach, the specific aspect of technical feasibility is purposefully excluded. In other words, this work does not seek to deploy or assess a technological use-case on technology-augmented work. Instead, this work captures qualitative perspectives on current and future applications of technology augmented work configurations.

We conduct a contextual enquiry into OAS in three stages: (1) a systematic literature review; (2) an exploratory qualitative study encompassing industrial practitioners across hierarchies of production companies; and (3) ethnographic observations in industrial education (Fig. 1). The review and fieldwork contributes to three areas in HTI research. Derived from different stakeholder groups this work: (1) compares how different perspectives of stakeholder groups in organizational hierarchies align with or diverge from each other; (2) explores work contexts which could be augmented by worker assistance in human-centric production systems; and (3) provides an integrative orientation for selecting projects in future HTI research such as mock-ups, prototypes or pilots (Heinrich & Richter, 2015).

This work is organized as follows: section 2 reviews HTI and OAS in industry. Section 3 discusses the research design in this paper. Section 4 synthesizes insights gained during the research. Section 5 discusses the implications of contrasting stakeholder perspectives on HTI in industry. Further, it reflects upon the challenge of integrating augmenting technology on the shop floor and into industrial education. Moreover, limitations and future research will be discussed. Finally, the conclusion summarizes the immediate as well as broader implications of this work.

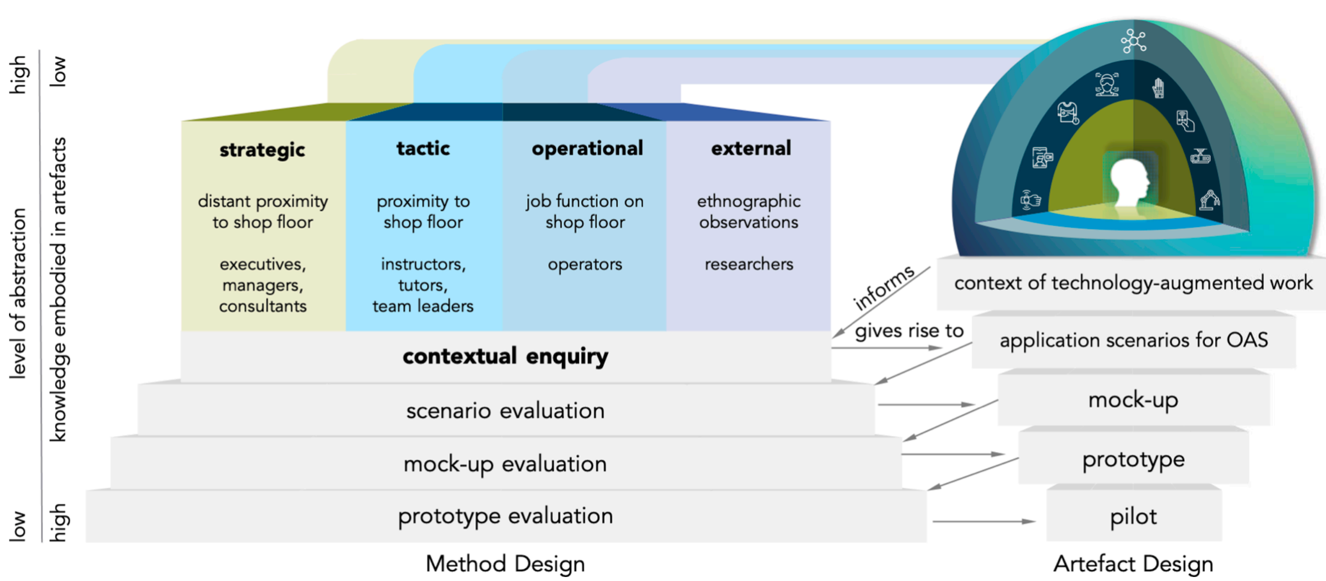

Fig. 1. Artefact-method co-design: illustrating the relationship between the iterative solution and method design phases of HTI in industry. Contextual, cross-hierarchical enquiries serve as a starting point for a human-centric, value-driven HTI journey (building on Heinrich & Richter, 2015).

2. Related work

This section introduces (a) the applied review method, (b) relevant terminology, (c) the concept of assistance systems in industry, (d) recent advances in industrial HTI research, and (e) the research gap which is addressed by this paper.

2.1. Review method

In order to identify and present relevant work, we conducted four inquires covering relevant areas of this research, encompassing 22 keywords (see Table 1) (Fink, 2014).

2.2. Terminology

In industry, an operator is a human who performs a specified type of job or who works in a specified way. Related work typically refers to *manual operators* or *blue collar workers* if an operator is primarily executing physical work tasks (e.g., operating certain physical equipment or machines) (Drucker et al., 1999). Conversely, *knowledge operators* or *white collar workers* are operators whose main capital is specialized (often technology-related) knowledge; their line of work primarily requires them to 'think for a living' (Drucker et al., 1999). An assistance system is a technical system that supports a human agent by sharing workloads (Wandke, 2005). As most existing technical systems strive to *ease the workload* of an operator, a higher level of detail is needed for an applicable OAS definition. (Wandke, 2005) introduced two further attributes of assistance systems: *human–computer interaction* and *function access*. First, an assistance system needs to provide an interactive interface between the operator and a technological system. Building upon Wandke (2005), Timpe (2016) depicts eight capabilities that may be augmented by OAS: *perception*, *sensory-motor functions*, *motivation*, *learning*, *thinking*, *problem-solving*, *decision-making* and *language*. However, functional access may only be realized under three circumstances: the capability must *exist*, the user must be *aware* of its existence, and its usage must *not exceed* the sensory, motor or cognitive capability of the user (Trotha, Azarmipour, & Epple, 2018). The latest aspect points to the consensus that the degree of assistance must be adequate for the intended use and context (Hold, Ranz, & Sihn, 2016).

Beyond the focus on providing the right information to the operator in an adequate way, related work associates a variety of attributes to the concept of OAS (Table 2).

For instance, in some work the underlying technology applied to realize the OAS or additional attributes are also integrated into the definition of OAS. We acknowledge that the terms *worker support* or *Operator 4.0* (Sun, Zheng, Gong, Paredes, & Ordieres-Meré, 2020) are frequently used in the literature when referring to OAS. Nonetheless, we argue that the term *worker* is often associated with a manual, non-skilled profession, thus diminishing the value and essential necessity of humans on the shop floor (Moencks et al., 2020; Pfeiffer, 2016). Likewise, concepts like *Operator 4.0* may imply an inherently technology-driven connotation where advances of the Fourth Industrial Revolution are assumed upon humans (Romero et al., 2020).

Taking into account all of the above, we conceptualize industrial OAS as *human-technology systems which interact with operators aiming to (a) complement, (b) positively modify or (c) augment the operator's cognitive or physical abilities whilst performing a certain range of activities in industry.* At the same time, an OAS is also a cyber-physical system that is, in turn, embedded into a larger industrial system such as a production system. It generally interacts with other systems (similar or not) in a dynamic industrial context (Fig. 2). The industrial areas of technology augmentation may be subjected but not limited to:

- labor and process optimization;
- industrial education and knowledge management;
- human operator protection such as ergonomics, operational health and safety, mental well-being; or
- operational control over an industrial system (e.g., a plant).

Table 1
Systematic of literature search.

Keyword	Inquiry 1	Inquiry 2	Inquiry 3	Inquiry 4
1	Production system*	Human skills	Manufacturing skills	Worker support systems
2	Cyber-Phys* produc*	Tasks	Future skills	Production assistance
3	CPPS	Activity	Future work	Intelligent worker support
4	Digital twin	Industrial skills	Human role	Human activity recognition
5	Industry 4.0	Learning	Human-centric	Technology acceptance
6	Automation maturity		Human-centered	

2.3. Industrial context

In order to address the question of where OAS could augment operators, it is helpful to look at the work areas of operators that typically occur in manufacturing. In general, the set of activities in production typically relates to either (a) production organization, (b) development, (c) procurement, (d) production or (e) quality control (Becker & Stern, 2016). Most of the value adding activities in traditional production companies can be assigned to manufacturing (Womack, Jones, & Roos, 1992; Sainsbury, 2020). The area of production can be subdivided into (a) manufacturing organization, (b) maintenance, (c) manufacturing of components, (d) assembly, and (e) operations and logistics (Becker & Stern, 2016).

Manufacturing organization includes tasks such as the design of the shop floor and logistics planning or alternatively the strategic, operational or tactic control tasks and activities in manufacturing environments (Reinhart, 2017). *Maintenance* comprises the set of activities and measures related to the preservation and restoration of the nominal state of technical means, as well as the measures for the determination and evaluation of the actual state of these means (Strunz, 2012). Here, the *manufacturing of components* includes processes of creating discrete products which are geometrically determined: objects having certain dimensions and shapes. *Assembly* refers to both the process of combining components into a product and to the auxiliary work that is necessary during and after manufacturing. Lastly, the transport, storage and delivery of materials within the sub departments or physical boundaries of a company can be referred to as *operations and logistics* (Reinhart, 2017).

Another important concept that needs to be mentioned in the context of OAS in industry is the technological-fix or technology-solution bias which relates to having a basic premise to find a technical solution to a problem. Although it is largely agreed that many problems are manageable with a technological solution, it needs to be critically scrutinized as to whether an OAS is the most efficient alternative within the entire solution space (Hagen, Nitschke, Schlindwein, & Goll, 2018).

2.4. Advances in operator assistance systems

As depicted in Table 3, we reviewed OAS for both cognitive and physical support, as well as for the designated areas of the shop floor and manufacturing learning. We classified the work reviewed as *technology-driven* if (a) the sought improvement or feasibility study is mostly technology related or (b) we could not find any explicit evidence that operational workers or end users significantly participated in the study throughout the entire process of the technology development. We defined work as *human-centric* if there was an explicit participation of operational workers or end users.

In general, OAS in industry are anticipated to (a) support the operator's abilities or capabilities, (b) provide situational, low-latency or

Table 2
Mapping attributes of operator assistance systems.

Attribute	Subject	Deployment Area	Description of support	Contribution	Technology
Intelligent (Bertram et al., 2019; Pacaux-Lemoine et al., 2017; Belkadi et al., 2020)	Operator (Pusch et al., 2019)	Knowledge (Tinz et al., 2019)	Assistance (Müller et al., 2018)	System (Bertram et al., 2019)	Augmented reality (Barbieri et al., 2019)
Context-aware (Alexopoulos et al., 2016)	Worker (Dhiman & Röcker, 2019)	Maintenance (Masoni et al., 2017)	Support (Cazzolla et al., 2018)	Tool (Barbieri et al., 2019)	Virtual reality (Holubek et al., 2019)
Cognitive (Kritzler et al., 2019)	Human (Kadir et al., 2020; Cimini et al., 2020)	Assembly (Müller et al., 2018)	Help (Huber & Weiss, 2017)	Framework (Peruzzini & Pellicciari, 2017)	Mixed reality (Wang et al., 2018)
Physical (Aaltonen & Salmi, 2019)	Expert (Wurl et al., 2019)	Learning (McGill & Klobas, 2009)	Aid (Boring et al., 2015)	Guidance (Ladwig et al., 2019)	Wearable (Salvadore et al., 2020)
Cyber-physical (Sun et al., 2020)	Operator 4.0 (Romero et al., 2020)	Ergonomic (Manghisi et al., 2019)	Management (Tinz et al., 2019)		Machine learning (Roth et al., 2020)
Human-centric (Kong et al., 2019; Peruzzini & Pellicciari, 2017)		Process (Murauer & Pflanz, 2018)			Co-bots (Sipsas et al., 2016)
Smart (Cimini et al., 2020)		Remote (Masoni et al., 2017)			
…	…	…	…	…	…

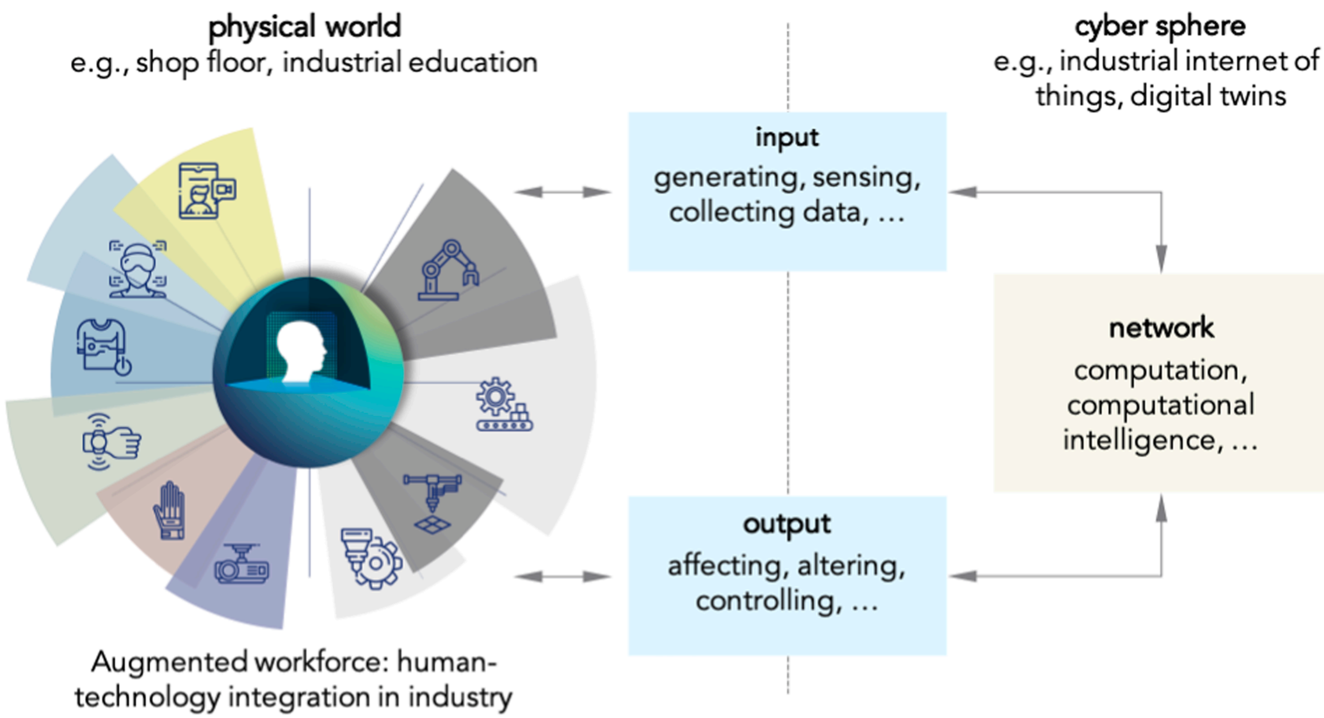

Fig. 2. Human-technology interaction in Industry: operator assistance systems connecting the physical world and the cyber-sphere in a production system, allowing for workforce empowerment and enhanced business excellence.

real-time feedback, (c) flexibly suggest next process steps while having a certain degree of context awareness, (d) monitor processes critical to quality, or (d) support the operator to perform a task in an ergonomic way (Hold et al., 2016; Choi, Hwang, & Lee, 2017; Erol, Jäger, Hold, Ott, & Sihn, 2016; Günthner, Wölfle, & Fischer, 2011; Holland, 2016; John & Wheeler, 2015; Stiefmeier, Roggen, Ogris, Lukowicz, & Troster, 2008; Sultan, 2015). For example, previous work on exoskeletons addressed the issue of ageing operators in terms of their decreasing physical ability with age (Weidner & Karafillidis, 2018). Especially in learning environments, the adaptability of CPPS is often emphasized as this allows for individualized learning progress of students (Roth & Moencks, 2021; Holland, 2016; Stiefmeier et al., 2008; Sultan, 2015). An ongoing research interest in the field of OAS can also be seen in the development of context-awareness: systems need to become aware of tasks and activities currently carried out by operators (Roth et al., 2020).

Although the reviewed work places the human in the center of work, we argue that in the majority of cases the focus lies with the development of a technology or its applicability in specific contexts (Fantini, Pinzone, & Taisch, 2020). Referring to Roger's argument of *technicity* (Rogers, 2003) or technology-centricity, research on OAS often appears to justify the utilization or enhancement of a specific technology rather than questioning whether there is a better (non-technological) alternative to a OAS before conducting their research (Dartt et al., 2009; Günthner et al., 2011; Hold et al., 2016; Rügge, Ruthenbeck, Piotrowski, Meinecke, & Böse, 2009).

In a value-driven or technology-neutral approach to HTI, the integration of OAS would begin with creating a concise understanding of the underlying problem space to be addressed (Moencks et al., 2021; Romero, Stahre, & Taisch, 2020; Cimini et al., 2020). Organizational factors are considered to be an essential success factor for realizing technology-augmented work configurations (Masood & Egger, 2019). Therefore, understanding the problem space needs to consider the cross-

Table 3
Mapping OAS application and tendency.

Source	Application	Support	Outline	Tendency
Hold et al., 2016	Shop floor	Cogn.	Concept of assembly assessment	Method-driven
Dartt et al., 2009	Shop floor	Phys.	Autonomous ergonomics assessment	Technology-driven
Choi et al., 2017	Shop floor	Phys.	Acceptance of safety OAS in construction	Human-centric
Günthner et al., 2011	Shop floor	Cogn.	Wearables for mobile scanning	Technology-driven
Rügge et al., 2009	Shop floor	Cogn.	Wearables in logistics	Technology-driven
Yam et al., 2001	Shop floor	Cogn.	Decision support for condition-based maintenance	Technology-driven
Stiefmeier et al., 2008	Shop floor	Cogn.	Context-aware wearable support system	Technology-driven
Lindberg et al., 2016	Education	Phys.	Education with games and wearable technology	Technology-driven
Sultan, 2015	Health care	Cogn.	Wearables for healthcare Education	Technology-driven
Holland, 2016	Education	Cogn. & Phys.	Wearables for next-generation education	n.a.
Erol et al., 2016	Education	Cogn. & Phys.	Learning factory	Technology-driven
Keeble, 2017	Education	Cogn.	Collective learning of technical industry experts	human-cenctric
hu Li et al., 2017	Generic	Cogn. & Phys.	Applicability of AI in induytry	Technology-driven
John & Wheeler, 2015	Education	Cogn.	Digital technologies for classroom Education	n.a.
Weidner & Karafillidis, 2018	Industry	Cogn. & Phys.	Review, presentation and evaluation of CPPA	n.a.
Kaasinen et al., 2020	Shop floor	Cogn.	Operator engagement into OAS	Human-centric
Pacaux-Lemoine et al., 2017	Education	Cogn.	Evaluation of manufacturing systems design	Human-centric

hierarchical perspectives of stakeholder groups (Moencks et al., 2020) However, after reviewing the OAS-related literature, we argue that work which integrates different hierarchical levels of organizations in the question of how to utilise technology is still scarce (Moencks et al., 2020). This in turn leads to the research gap we strive to address in this paper: cross-hierarchical, contextual enquiries on OAS in industry.

2.5. Research gap

Despite some human-centric approaches to OAS in industry, we argue that many contributions still implicitly take on a technology-driven perspective with the assumption that there is a stage of technology acceptance that ultimately has to be reached and that technology is the most effective solution for a challenge. For example, in some cases the underlying research question states the purpose for which a (specific) technology can be utilized. Moreover, we identified that human-centric technology development projects often inquire about the operational workers' perspective and attitude towards a technology. We could not identify work which considers the various stakeholders in the different hierarchical or strategical levels in organizations (strategic, operational, tactical) — this applies to both the shop floor and industrial learning environments. In other words, there is a research gap in exploring the perspectives of different hierarchical levels in organizations towards the application areas of technology to augment human abilities in human-centric production. This in turn gives rise to a guiding research question: **in the context of HTI and technology-augmented work in industry, where can organizations leverage OAS to augment their manufacturing workforce?**

In order to sufficiently address this question, it is divided into three research questions delineated in the following:

1. How do cross-hierarchical stakeholders characterize the role of the human operator and technological artefacts on future shop floors?
2. In which contexts of daily business and industrial education would stakeholders be open to leverage OAS?
3. How do cross-hierarchical stakeholder perspectives on OAS applicability align, and how can this alignment influence future technology deployment projects?

3. Research design

In the following section, we will outline how our research will address the identified research gap. It encompasses the specific objectives of the research process, specifies the sources from which we collected data and depicts how we analyzed them. Additionally, we will discuss ethical issues (e.g., access to the data). Aligned with (Bower, 2019), our research follows a fundamental assumption: in both the technology-mediated learning context and technology-enhanced worker augmentation, the agentic intentions reside with humans and not with technology.

3.1. Philosophy and methodological choice

Following *interpretivism*, we strive to make sense of subjective and socially constructed meanings (Saunders, Lewis, & Thornhill, 2016). Thus, we consider it useful to leverage more than one qualitative data collection technique and corresponding analytical processes resulting in a multi-method qualitative study. An exploratory study is considered particularly useful when striving to gain insights about a topic of interest whose nature is not yet fully understood. Moreover, exploratory research has the advantage that it is flexible and adaptable to change (Saunders et al., 2016). Following this, we decided to utilise an exploratory approach to address this research gap.

3.2. Semi-structured expert interviews

The interviews conducted within our study followed the method of (Söderblom, 2007) and are based on an interview guideline with open-ended questions. The questions aim to generate as specific and relevant answers as possible. Moreover, the questions need to be sufficiently concrete with regard to the research subject. However, questions must not lead to a suggestive influence of the interviewee. In order to ensure this, the comprehensibility and coherence of the questions were pre-tested with two independent participants. These pre-tests allowed for a minor modification of the questions regarding their choice of words as well as the construction of the final guide (Söderblom, 2007).

3.3. Interpretive ethnography

In addition to collecting qualitative impressions of individuals, it is useful to gather additional first-hand experiences in industrial environments. This allow us to (a) further reveal aspects and dynamics relevant to participants' statements; (b) reflect on the insights provided against the background of the circumstances in which they were created; (c) formulate inter-subjective impressions of the research topic; and (d) reflect on coherence and individual references (Saunders et al., 2016).

Ethnography can be used to study the social world of a group. As we assume that there might be multiple or pluralistic meanings and perceptions of HTI, we follow the approach of interpretive ethnography (Delamont, 2004). In this paper, subjective ethnography aims at revealing aspects and dynamics relevant to participants' statements and reflect those against the circumstances in which they were created. Hence, we integrate ethnography into the results without explicitly pointing out individual observations.

3.4. Data configuration

For each perspective in an organization, we considered a different set of individuals by relying on purposeful sampling (Easterby-Smith, Thorpe, & Jackson, 2012; Saunders et al., 2016). We aimed to interview individuals with a variety of experiences. Each participant was assigned to one sample group corresponding to the different perspectives on OAS in organizations: (1) strategic management, (2) tactical industrial instructors and (3) operational industrial operators. The interview process of the different sample groups is part of the same multi-method qualitative study. However, to reach a higher degree of readability, the different interview processes of the samples are solely referred to as study 1, 2, and 3. As shown in Table 4, the data set comprises perspectives from various sectors and functions in industry: automotive, aviation, special machine construction, industrial consulting, industrial research, industrial instructors, and apprentices. To identify which respondent provided the related information, the interviewees' statements are referred to in a standardised format, i.e., "I-#-Statement" where "#" corresponds to the interviewee in Table 4 (e.g., I-1-005 – interviewee 1, statement 5).

Within the interpretive ethnographic observations, we observed (1) benching: a practical course where students acquire manufacturing skills like manual filing or manual bending, (2) an operational excellence/ lean production course: a medium-level course mandatory for most apprentices where classical approaches to lean philosophy are taught in a combination of theoretical learning and case studies and (3) a project management for engineers course: an advanced course attended by fully trained engineers (practically trained or with a non-academic career path) who continue their education in project management. The observations were recorded in the form of memos and then transformed into an observation protocol.

3.5. Interview guidelines

In order to provide a comparable framework for the studies, the beginning and the completion of the guideline for study 2 and 3 is derived from its respective counterpart in study 1. The guideline encompasses elements such as the discussion of formalities, the evaluation of previous experience, the future of production as a first dimension of analysis as well as the inquiry for further contributions, further contacts and a debriefing in the end (Appendix).

During the collection of primary data, asethical issues are important to address. Throughout the entire research, we strictly followed the ethics guideline of the University of Cambridge.

The interview guidelines were pre-tested with two individuals (a potential participant in the field and an experienced research fellow). The final coding scheme of the qualitative data can be found in Table 5.

Table 4
Configuration of primary data.

#	Perspective	Industry/ Sector	Function/ Focus	Duration [min:sec]
1	Strategic	Research	Production Management, Technology and Tooling	20:46
2	Strategic	General Manufacturing	Learning Factories	26:04
3	Strategic	Research and Consulting	Digital Assistance Systems for Assembly	17:31
4	Strategic	Automotive Research	Production Systems and Digital Twins	21:27
5	Strategic	Automotive	Head of Production System	23:47
6	Strategic	Automotive	Plant Director	14:05
7	Strategic	Aviation - Helicopters	Ergonomics in Production	34:30
8	Strategic	Machine Construction	CEO	32:14
9	Strategic	Industrial Education	Head of Training Centre for Apprentices	52:15
10	Tactic	Industrial Education	Instructor for Robotics and Programming	31:58
11	Tactic	Industrial Education	Instructor for Project Management	41:52
12	Tactic	Industrial Education	Instructor for Business Improvement	31:13
13	Tactic	Industrial Education	Instructor for Lean Production	47:24
14	Tactic	Industrial Education	Higher Education Program Lead	30:54
15	Tactic	Industrial Education	Instructor for Benching, Filing, Bending	30:08
16	Operative	Automotive	Apprentice in Manufacturing and Engineering	24:01
17	Operative	Food Industry	Apprentice in Manufacturing and Engineering	30:33
18	Operative	Automotive	Apprentice in Mechatronics and Maintenance	16:25
19	Operative	Automotive	Apprentice in Measurement and Data Analysis	18:42
20	Operative	Food Industry	Apprentice in Manufacturing Engineering	13:14
21	Operative	Consumer Goods	Apprentice in Maintenance and Engineering	21:12
22	Operative	Generic	Apprentice in Maintenance Engineering	15:48
23	Operative	Food Industry	Apprentice in Engineering and Manufacturing	24:20
24	Operative	Aerospace	Apprentice in Applied Engineering	28:11
25	External	Industrial Education	Ethnography: work bench	900:00
26	External	Industrial Education	Ethnography: lean manufacturing	480:00
27	External	Industrial Education	Ethnography: project management	540:00

Table 5
Coding scheme of the qualitative data.

Background	Future of Industry	Manufacturing Skills	Assistance Systems	Challenges
executive	technology-driven	current relevance	cognitive support	errors
manager	human-centric	future relevance	physical support	learning challenges
researcher	trends	technical skills	exception management	shop floor challenges
consultant	industrial learning	soft skills	standard operating procedures	value-augmentation fit
instructor			data handling	knowledge transfer
student			digital engineering	technology limitation
Interaction	**Integration**	**Human Role**	**Technology Acceptance**	**Further Contributions**
automation	participating development	Assembly	Type of Support	Sustainability
collaboration	operator heterogeneity	Quality	Augmenting Abilities	Health and Safety
coexistence	concerns	Maintenance	Temporal Replacement	Social Implications
	Manufacturing	Inbound Logistics	Support Initiation Process	Talent Acquisition
	up-skilling	Control	Accepted Areas of Support	Political Influence
	respect	Teaching	Design Principles	

3.6. Qualitative content analysis

The choice of the evaluation technique for semi-structured interviews depends on the underlying objectives, the research questions and the methodological approach (Flick et al., 2002). Based on the approach of Mayring (2010), Kuckartz (2012) developed an altered version of qualitative content analysis. In both approaches, embedding the qualitative data into their communicative context can be seen as a central aspect of the analysis (Kuckartz, 2012). While the initial approach primarily focuses on classification and counting categories' frequency of occurrence, Kuckartz (2012) proposes a more case-oriented approach. The content-structuring qualitative content analysis is considered suitable for research purposes that focus on the systematisation and analysis of content that is expected to have reciprocal relations (Mayring, 2010; Kuckartz, 2012). Section 4 is organised in accordance with the interview guideline we followed (Appendix).

4. Results

4.1. Quantitative analysis

By solely taking into account the relative amount of coded lines per main theme (or Total Coding Density per Main Theme - TCDMT), it can be seen that the qualitative study primarily covers three issues (Table 6): (1) OAS (TCDMT: 21.2%), (2) future of manufacturing, production and industrial learning (TCDMT: 19.9%) and (3) Manufacturing Skills (TCDMT: 17.2). Moreover, the case-specific coding density per main theme (CSCDMT) reflects the intended dimensions of analysis for each case. Study 1 emphasizes strategic challenges (CSCDMT: 24.0%) and possibilities to address these challenges with OAS (CSCDMT: 24.0%), whilst study 2 intended to explore major task areas for possible OAS (Role of Operators in Manufacturing organization - CSCDMT: 27.8). In study 3, emphasis was placed on the technology acceptance of the operator (CSCDMT: 23.2%). The quantitative analysis of the data indicates that the research design introduced above is suitable to address the research questions subjected to this paper. In general, participants of the different studies tend to comment most on the themes which are likely to be associated with their respective area of responsibility and expertise.

Table 6
Quantitative analysis of cross-hierarchical stakeholder perspectives: coding density per main theme.

Main Theme	Study 1	Study 2	Study 3	Total
Future of Industry	18.0%	26.2%	16.0%	19.9%
Manufacturing Skills	18.0%	11.1%	15.2%	17.2%
Operator Assistance	24.0%	19.8%	19.2%	21.2%
Challenges	24.0%	9.5%	12.0%	11.0%
Interaction Modus	11.3%	3.2%	4.0%	6.7%
Integration	12.0%	0.8%	0.0%	2.0%
Operator Role	4.7%	27.8%	10.4%	12.0%
Technology Acceptance	6.0%	1.6%	23.2%	10.0%
Total	100.0%	100.0%	100.0%	100.0%

4.2. Future of technology-augmented work configurations in industry

When looking into the anticipated future of manufacturing and production, the strategic participants appear to take on positions that are comparatively aligned. In general, participants belonging to the first focus group tend to characterize the future of manufacturing and production with terms or concepts related to either **complexity** or **efficiency** (cf. I-1-001; I-1-005; I-3-003; I-2-002.) While these drivers seem to be the most relevant factors, strategic participants also partly mention the aspect of **sustainability**: "I think one major issue is greener production. That is, companies are focusing more to produce without having any impact on the sustainability. Additionally, it's about the digitisation" (I-2-002).

4.2.1. Strategic perspective

Although the **strategic participants** are largely in agreement that there will not be many **lights-out factories** (see I-2-003), manufacturing organizations will continue to reduce the number of manual tasks that might be classified as comparatively easy or repetitive. Moreover, respective manufacturing companies expect an increasing demand of highly qualified operators. Three main reasons can be related to this expectation: (1) the trend of *production on demand* (see I-5-003), (2) the associated objective of producing with lot sizes of 1 entity as well as (3) the increasing complexity of the inherent characteristics of existing products (see I-6-002). Due to the increase of products and production complexity, participants anticipate that it might become more challenging to effectively run a production system (cf. I-1-003; I-5-004). This, in turn, will require (technological) assistance to support the operator in handling the complexity, as exemplified by this statement: "In general, I would say that assistance of workers and future production environments will get more and more important because [of the] more complex work they have to do." (I-3-003).

4.2.2. Tactic perspective

The group of **tactic participants** might be characterized by a more heterogeneous spectrum of perspectives on the general future of manufacturing. In other words, the statements of tactic participants addressing this main theme appear to partly contradict each other (cf. I-13-002; I-15-002; I-9-002). Some participants perceive an ongoing, positive and operator-focused development on the shop floor by pointing out the increase of occupational health and safety as well as a higher degree of effectiveness and efficiency by supporting the operator on the shop floor. In the context of assistance on the shop floor, a subset of participants accentuate the increase - or the introduction - of approaches related to data management. These participants seem to characterize the future of manufacturing as an ongoing, but **moderately paced evolution**. According to their position, technology might play a more important role within the next decades; the technology itself, however, will be introduced to support operators in performing their manufacturing tasks (see I-10-011; I-9-002; I-12-003).

4.2.3. Operational perspective

In general, the **operational participants'** perspective on the future of manufacturing and production appears to lean towards a **robotized** scenario; according to some operators, humans will primarily carry out maintenance, problem-solving and handling of equipment on future shop floors. Similar to participants in study 2, it appears that there are different anticipations for the introduction of technology: some participants see technology as an opportunity to support or enhance operational work, whilst other participants consider current advances in technology as precursors of complete automation of production: "I think the future of manufacturing is heavily headed towards being automated. Never completely automated because human power is going to be behind a lot of things always" (I-19-002).

4.3. Future of industrial education

Strategic participants rarely touch upon the future of industrial learning or learning programs (CSCDSC: 3.76%). Rather, the strategic participants focus on the skill set of employees, which is anticipated to be required in the future.

The data indicate that the sector for industrial education or industrial learning will eventually **adopt to the requirements** and needs of the respective industry sectors. Tactic participants state that industrial education has to be seen as a supplying sector which adapts its curriculum according to the needs of industry. This phenomenon can be characterized as the principle of customer centricity and might have two implications. First, the sector of industrial education does not appear to push new trends, skills or knowledge into the industry. Second, industrial education follows the need for technology skills articulated by industry to implement respective technology. These process steps appear to influence each other, resulting in the deceleration of technological innovation diffusion: "Training is specifically about providing needs for industry today, not about tomorrow. And again, that's one of the reasons why I think [the] growth [of] technology implementations cannot be that fast." (I-09-002).

In the context of strategy for knowledge transfer, participants' perspectives seem to differ. To a certain extent, these scenarios could even be characterized as diametrically opposed. Some instructors see a significant increase of **technology-mediated knowledge transfer**; for example, experts anticipate that "[…] simulation and simulated experiences will become the norm" (I-12-005). While others support the idea that technology is going to play an increasingly important role, they merely see technology as an additional medium to convey knowledge. This latter perspective is often represented by instructors which also emphasize the importance of interpersonal interaction.

In general, operational participants' perspective on the future of industrial education suggests that industrial courses will continuously adapt to the need of companies as well as to relevant technological changes (e.g., I-17-004). According to participants of focus group 3, the "[…] old fashioned spectrum of apprenticeships is still kind of […] present in the future" (I-21-004). Additionally, participants noticed an ongoing decrease of theoretical content or classroom-based learning within their apprenticeship programs and instead practical or hands-on learning began to play a more important role in their program's curriculum (e.g., I-16-005). The operational students, furthermore, see a significant increase of **technology-mediated learning** scenarios in the future (e.g., I-19-005). Anticipations encompassing technology-mediated learning scenarios are often followed by implicit expressions for desirable changes of the current learning experience. For example, operational participants express that technology-mediated learning could foster a more individualized learning experience (e.g., I-21-007; I-18-008), a more efficient or standardized way of learning (cf. I-18-008; I-19-005) or a more convenient access to the content and knowledge (e.g., I-21-004).

4.4. Skills in future manufacturing

Skills Portfolio. In the context of manufacturing skills, participants anticipate an ongoing transformation or a distinctive change of the *skills portfolio* (I-5-006) that will be required for operators in the future of manufacturing (cf. I-3-007; I-5-006; I-6-004; I-11-007; I-14-005; I-19-006). In general, participants predict a continuous reduction of the execution frequency of *simple* (I-13-009), *easy* (I-1-005) and *repetitive* (I-5-007) tasks for operators on shop floors. However, as discussed in the following section, depending on the respective group both the perceived importance of current manufacturing skills and the anticipated direction of the skill portfolio transformation tend to vary.

According to participants in study 1, trends related to the concept of Industry 4.0 result in an increased demand for operational workers with technological understanding, knowledge about emerging technologies and advanced practical engineering qualifications (cf. I-1-005; I-2-008; I-3-007; I-5-007. These changing requirements for manufacturing workers might influence both the operational work space and the tasks along the entire value stream within and across organizations (I-1-005). In other words, participants expect that the ongoing acquisition of cutting edge, **explicit knowledge** is mandatory for workers regardless of their hierarchical position. In many cases, participants emphasize the importance of standards and improvement: working with standards, continuous standardisation, continuous improvement and development of standards, as well as the reliable execution of standardized tasks (I-1-007; I-4-005). Besides the importance of *working by standards* (e.g., I-6-004; I-1-007) and the *continuous improvement* (I-4-002; I-13-010), participants postulate an increasing demand for manufacturing skills related to exception and error handling of highly automated processes, as exemplified below: (a) "We'll see […] the human task shifting to exception handling, error handling, control and improvements on the processes" (I-2-003) and (b) "[I]t's not so much about executing the task, but rather about being able to detect when things get out of boundaries" (I-3-005).

Social and Technical Skill. While pointing out the transformation of technical skills in current and future manufacturing, participants in study 1 rather emphasize the importance of social skills that are related to creativity, behavior and attitude. For example, areas such as machining technology, control technology or programming can be characterized as technical skills that might become requirements for workers' skill portfolio (cf. I-6-003; I-8-005). However, participants accentuate the importance of the creative handling, the analysis and the effectuation of data available on the shop floor, rather than the actual skill of programming (I-8-005; I-9-004). Strategic participants point out the importance of **skills** related to team leadership, communication, motivation, adaptability and management (cf. I-9-004; I-7-006; I-8-005). However, it is worth mentioning that we could not find evidence that participants expect any change in the required set of social skills that are related to behavior and leadership (I-9-004; I-7-006; I-8-005), implying that while the demand for certain technical skills or methods might change in the future of manufacturing, participants do not anticipate a change in the already high demand for operational workers that are driven to improve the status quo on the shop floor.

Regardless of automation trends in Industry 4.0, tactic participants in study 2 expect an ongoing need to convey traditional manufacturing knowledge to operational workers and an ongoing need to teach **practical manufacturing skills** (cf. I-10-004; I-13-010; I-15-003). In particular, skills which are related to *hand-eye coordination* are not expected to change in the near future (I-15-003). The reason for this can be seen in one of the enablers of continuous improvement: process understanding. Even if the entire production process was fully automated, participants assume that the remaining workers or engineers still need to have a detailed understanding of the individual machining steps, as exemplified by the following statement: “They do bench skills. They do milling and turning, electrical maintenance, mechanical maintenance. They do mechanics and hydraulics. […] I doubt bench work milling and turning will become obsolete in the future, even if they'll [manufacturing processes] become automated. But, you know, people will still need to know what those machines are doing” (I-10-003).

4.5. *Work on future shop floors*

According to participants, the major purpose of a human-centric OAS is to support operators whilst carrying out certain manufacturing tasks in certain work areas (see I-1-011; I-3-003; I-4-012; I-20-003). Thus, we investigated the generic work areas in future manufacturing environments where operators are anticipated to play a significant role.

4.5.1. *Manufacturing organization*

In the context of manufacturing organization, it is anticipated that operators will continue to control operations on the shop floor. Given a sufficient amount of data, an advanced OAS is expected to take over a certain degree of control over the shop floor. However, the type of control is considered to remain of indirect nature; OAS are going to be deployed to effectively transpose operators' intentions rather than realizing own decisions. For example, an OAS might verify operators' compliance with a standard working procedure (see I-1-017). Moreover, as repetitive or simple tasks in manufacturing are expected to be taken over by autonomous machines, remaining operators on the shop floor are anticipated to have a comparatively higher qualification. Regarding the manufacturing organization, participants therefore see an increase of tasks related to conceptual work such as **diagnosis** (I-10-016), technology-assisted planning, steering of production processes (I-3-008), complexity management (I-5-003), monitoring (I-13-023), unconventional problem-solving (I-14-018) or creative forecasting (I-12-028).

4.5.2. *Maintenance*

When asked for an assessment of the future role of the operator in the work area of maintenance, participants depict a highly integrative scenario. Despite the advances in digital technology and automation, the demand for operators to maintain production facilities will remain on a high level (see I-11-014; I-12-021; I-4-008; I-8-015; I-10-010; I-15-011; I-18-003; I-14-013), while the data-based identification of objects that need to be maintained is going to be done by OAS (I-4-008; I-15-011). In combination with increased process reliability of machines, participants expect a decrease in the total number of machine failures and maintenance operations (I-10-010; I-11-014). However, as the nature of the remaining activities becomes **more complex** it is expected that maintenance tasks are going to be executed by (highly qualified) operators (I-17-003; I-10-010; I-15-011).

4.5.3. *Manufacturing of components*

It is anticipated that in the work area of manufacturing of components both the number of operators on the shop floor and the amount of manual tasks will significantly decrease (cf. I-15-012; I-10-011), which will be particularly caused by the expected advances in additive manufacturing technologies such as additive manufacturing and the trend of automation (I-12-023). According to participants, operators will be involved in the design phase of manufacturing processes and product development tasks such as constructing, prototyping and validating (see I-11-016; I-12-023). Once a product is ready for series production and the process is considered controllable to a sufficient degree, the actual process of manufacturing the required components will be executed by **(semi-) autonomous machines** (I-14-014). However, in production scenarios that are characterized by low volume and high complexity, the need for highly-skilled, technical operators remains (I-10-011): “So, they're [operators] actually looking over and owning the process [of manufacturing components], not just operating the process” (I-12-024).

While participants' expectations for previous work areas coincided, some divergent anticipations regarding the work area assembly could be identified. In general, most participants in studies 1 and 2 express the **essential necessity for operators** to remain in assembly operations as the inherent complexity and variance of assembly tasks would require trained skills and experience that cannot be easily replicated by autonomous machines (see I-3-008; I-5-008). Moreover, the future reduction or automation of human activities in assembly seems to be particularly challenging for industries that can be characterized by low product volumes, high variance, high quality requirements or one-off procedures (cf. I-10-009; I-11-012). Since autonomous machines are not primarily built for exception handling, robots are not expected to take over the entire set of assembly operations on future shop floors (I-19-007).

4.5.4. *Operations and logistics*

In inbound logistics, there seems to be a consensus that the operational role of humans will become of **negligible importance** (cf. I-19-019; I-11-018; I-10-013; I-5-008; I-12-026). Participants agree upon the view that movement of goods will continue to be reduced to an absolute minimum whilst, for reasons of efficiency, safety or ergonomics, logistics processes such as the process of picking components are expected to become fully automated (I-10-014). However, according to participants, the strategic control over the material flow within the organization remains with the human (I-19-017; I-10-010).“Logistics and warehouses are usually robotized in our days, anyway. There are already very few human interventions. I guess there will be quite a few people overseeing it but there actually will not be that many people” (I-15-013).

4.6. *Applicability of operator assistance systems*

4.6.1. *Scenarios*

In general, the application areas for OAS mentioned by participants can be characterized as either (a) variety and exception handling, (b) support in standard operating procedures, (c) support of data analysis, diagnosis and optimisation or (d) technology-mediated learning, further education and digital engineering (I-2-009; I-11-017; I-13-005; I-12-015). Additionally, the type of support can be distinguished between cognitive and physical support (I-19-017; I-10-010). As stated below, many participants expect OAS to be a complementary support for operators on the shop floor. In the foreseeable future, therefore, the **operative control** of the shop floor stays with the operator, as exemplified in the following statement: “For the next 10 to 15 years, taking into account the current complexities, I cannot imagine that machines can [autonomously] control this manufacturing process and address these complexities; but digitalization needs to remain a tool to achieve goals, to enhance process designs, to combine processes and to allow for an overall efficiency” (I-6-009-translated).

4.6.2. *Physical assistance*

In the context of OAS, participants in study 3 often think of scenarios for physical assistance as being technologies like exoskeletons (I-18-019; I-20-004), although it might be worth mentioning that operational participants' overall opinion on physical support appears to be rather reserved or negative. In other words, when confronted with the choice between an ability enhancing exoskeleton and an autonomous robotic **lifting assistance**, participants tend to choose the latter, as described by the participant below: “Skeleton. It is like becoming Iron Man! [laughing]. I think, innovation wise that's very cool. However, I don't know if I'd feel completely comfortable being engulfed by an artificial strength” (I-19-017).

4.6.3. *Working by standards*

Participants in study 1 often emphasize the importance of working by standards in manufacturing environments (I-1-008; I-4-007). Moreover, respective participants expect an increase of complexity in manufacturing processes, reduction of lot sizes as well as an increase of product variation (I-3-003; I-6v005). From the perspective of the strategic participants, OAS could effectively address both issues thus ensuring standardized operating procedures in high-complexity and high-variety production (I-1-008). Therefore, an overall objective of OAS could be seen in “[…] **guiding the operator** through the process, more variable and more flexible” (I-3-011). For example, visual support such as visual reminders (e.g., short videos) of standard operating procedures for rare product variations could support the operator throughout the day. In the context of exception handling, a possible OAS should be seen as an optional, voluntary guidance system that can be used across typical manufacturing tasks in organizations such as assembly or inbound logistics (e.g., intelligent picking support) (I-2-009).

4.6.4. Exception handling

Another area of exception handling can be seen in unexpected multiple machine downtime or failures. In those cases, participants expect future OAS to assist in prioritization of downtime as well as support in diagnosis (I-2-009). Additionally, the issue of ergonomics and occupational health and safety seems to be of great importance for participants in study 1. Physical support systems in particular such as exoskeletons might prevent long-term injuries or enable elderly people to stay in workplaces that can be considered physically demanding (I-7-006; I-4-007). However, a major issue with OAS is seen in the **lack of robustness and high latency**, i.e, verifying that the system needs to ensure a seamless workflow for the operator.

4.6.5. Technology-mediated learning

From the perspective of participants in study 2, a major benefit of OAS could be an enhanced, technology-mediated learning experience in further education and support in digital engineering (I-10-007; I-11-006). It would therefore support the learning process of operators by visualization, simulation or individualized feedback. While some participants in study 2 expect OAS to have a positive impact on manufacturing learning, other participants are more critical. This is mainly due to a line of thoughts which could be derived by looking at the exemplary statement: “Thus, I need to get an economic benefit for the employer. […] I already have bricks and building sets. With those I can teach the principles […]” (I-9-010).

On the other hand, participants in study 3 appear to be generally open to being supported in their daily jobs by OAS. Recent advances in technology are perceived as actual support, rather than attempts to replace workers. participants further expect advances in technology-mediated learning, further education and digital engineering. More specifically, participants anticipate an **individualized, technology enhanced learning** experience. Participants appear to see a benefit for scenarios where the process of conveying knowledge is realized by a system that automatically adapts to the individual’s capabilities.

4.7. Collaboration and co-existence

In this work, the term *modus* refers to the way of interaction between humans and machines in manufacturing contexts, where participants tend to distinguish between (a) automation, (b) human-machine co-existence and (c) human-machine collaboration (I-1-014; I-11-004; I-12-002). The distinction is often made according to the degree of involvement of operators on the shop floor and their degree of local interaction with (semi-) autonomous machines or robots. According to participants, **human-machine co-existence** involves the cooperation of machines and operators in spatial or temporal separation - some participants also refer to this concept as *hybrid* or *mix*. Human-machine collaboration, on the other hand, refers to a scenario where humans and machines such as so-called collaborative robots (also: co-bots) are simultaneously carrying out manufacturing tasks with small or no spatial or temporal separation.

Initially, it seems that human-machine collaboration in manufacturing is considered to be an ideal scenario in future manufacturing; for example, the ergonomic support of co-bots is seen as a major benefit in manufacturing (I-5-011). Moreover, it can be seen that many operators in study 3 are generally open to working with collaborative robots to a certain extent and under certain conditions (cf. I-16-016; I-18-016; I-19-015; I-16-021). However, despite the ongoing advances in collaborative robotics, most of the participants anticipate human-machine co-existence or automation on future shop floors. In fact, some participants characterize the advent of **co-bots** as a short-term **hype phenomenon** (I-5-011). Four underlying reasons for this position have been identified: (a) strict regulations for occupational health and safety, (b) lack of scalability and limited business cases, (c) lack of intuitive control and feasibility and (d) restrictions by product and process properties.

Participants across the three studies point out that strict regulations for occupational health and safety (OH&S) are restraining the development and implementation of collaborative robot support systems, co-bots or body-worn OAS (cf. I-6-008; I-12-027; I-21-024). Following this, participants observe that companies - regardless of their size - stopped projects aiming for the implementation and development of co-bots (I-1-014).

Many participants mentioned ongoing research projects, piloting phases and showcases around co-bots, but could not think of organizations that evidently implemented respective systems within their serial production or their business processes (I-5-011). Furthermore, collaborative human–machine systems could be considered **case-specific niches** with restricted scalability (I-4-012): “[T]here’s also a lot to do in terms of how to make it happen and how to bring that really to life and not only to have niche showcases, technology exhibitions, but actually things that work 24-7 reliably in the actual context” (I-2-013).

Besides the challenges in regulation and the restricted applicability, the control of current systems is considered inadequate and non-intuitive: “I would say right now it’s mostly done poorly, especially in software programs used in production environments. I think this needs to be a lot more intuitive and easier; a lot more connected” (I-3-014).

4.8. Acceptance

In general, the main themes acceptance of technology and support may be divided into the following sub-categories: (a) type of support, (b) degree of machine involvement, (c) support initiation mechanism, (d) accepted areas of support and (e) design principles. It turns out that in the context of technology acceptance, some preferences seem to compete with each other; for example, some participants tend to welcome OAS which are supporting physically challenging work on shop floors (I-16-014; I-18-022; I-21-021). Other participants express their **reservations** about being supported in (physical and cognitive) tasks for which they received explicit training. However, it seems that participants agree with certain fundamental or basic design principles that need to be taken into account while developing OAS.

‘There are always employees who shout “Hurray!” and there are employees who do not want it [support] at all. That has a lot to do with individual gusto or preferences’ (I-5-013-translated).

The type of support describes the general nature of task areas or manufacturing skills where operators would potentially accept being supported by OAS and the type of support may be divided into cognitive or physical areas. Although participants in study 3 often think of scenarios for physical support, participants also see cases where **cognitive support** is considered to be beneficial (cf. I-16-014; I-16-016; I-17-010). For instance, participants expect physical support of OAS to prevent chronic injuries such as back pain. Moreover, OAS are anticipated to contribute to the overall enhancement of health and safety as well as ergonomic ways of working (I-16-014). Additionally, many participants value the opportunity to receive cognitive support by OAS in various forms: from calculators to complex diagnostic systems to support predictive maintenance (I-16-012; I-18-018).

The degree of machine involvement depicts the way of support that is preferred by operators. In other words, this part strives to investigate if operators prefer to (a) gather augmented abilities whilst applying OAS or (b) let an OAS take over a task, thus temporally replacing the function of the operator. In the context of human–machine interaction, this issue has already been briefly addressed. For physical manufacturing tasks, operators prefer a scenario where a machine takes over a respective task in **adequate spatial distance** to the operator (I-16-019; I-17-016). The following statement illustrates the justification for the preference of participants that let the machine take over: 'If the robot is doing it in its capability range, look, they can do it. But I'd rather see me doing it without the exoskeleton. But if it was too heavy for me to lift, the robot's doing it' (I-18-022).

Operators seem to expect a decrease of their natural abilities when relying too much on artificial support (see I-17-018; I-20-022; I-16-019). Moreover, participants do not consider it effective if a system is designed to enhance physical human abilities while a robot could do the identical task on its own. Consequently, participants seem to accept an OAS taking over on the shop floor and **temporally replacing** the function of the operator. As a result, participants tend to prefer an autonomous robotic lifting assistance which is not attached to their bodies over a body worn, ability enhancing exoskeleton (I-17-018).

Another important issue is the accepted support **initiation mechanism** of OAS, which refers to the exploration of whether operators accept an OAS that autonomously initiates a supportive procedure, or an OAS whose initiation process is controlled by the operator. According to the available data, the operational participants' perspectives seem to align: apart from OAS in industrial learning scenarios, participants strongly prefer a controlled support initiation mechanism (I-16-019; I-17-015; I-18-024; I-20-021; I-21-022). This is mainly due to two reasons. First, operators do not fully trust the ability of an artificial system to accurately assess when the initiation of support is appropriate. Second, some participants occasionally seek to challenge themselves. An autonomous support system might therefore limit the opportunities for individuals' self-directed development, as participants would rather "[…] push the button to be supported" (I-21-022).

"Okay, this sounds so stupid but personally, I'd feel like I was being not made fun of but feel stupid if it automatically did it for me. Because sometimes I can do it myself. I just have to think about it" (I-17-015).

"Potentially, it could become an annoyance having an automated response. Unless it's a learning program that learns your actions, what you can do. It might try and interfere more times when you need it" (I-21-022).

4.9. Industrial challenges

The major challenges mentioned by participants can be seen in (a) general challenges on the shop floor, (b) general challenges in industrial education and (c) cost-benefit and effectuation.

In general, challenges on the shop floor are likely to occur if a **standard operation procedure** is not consistently followed (I-1-013), or if there is a significant increase in the complexity and variety (I-5-012) of products and tasks. participants emphasize that the occurrence of errors is one of the natural consequences in non-automated work, but a challenge can be seen in detecting the errors as soon as possible in order to guarantee a quality standard to customers (I-6-006; I-3-012). On the other hand, in some industries the occurrence of errors related to operators seems to be of negligible importance. For example, due to rigorous safety regulations in the aviation industry, operational workers need to document the precise work done on the product (I-7-014).

When it comes to challenges related to industrial education, the key ones were **continuous adaptation**, **customer-centricity** and **engagement of students**. Additionally, introducing new products or variations requires additional training or qualifications, so one challenge therefore exists in the coordination and implementation of these continuous training courses (I-7-011). As participants characterize the industrial education sector as a service provider for manufacturing organizations, it results in two challenges: 1) institutions that specialize in the vocational training of operators need to constantly adapt to the demands of their customers (cf. I-7-011; I-9-006; I-9-008) and (2) it is considered relatively challenging to integrate new elements into the curriculum (e.g., technology-mediated learning applications), which does not immediately increase customers' willingness to pay a higher fee for the respective, modernized vocational training (I-9-006). Due to these major limitations, institutions in industrial education are more likely to respond to innovations instead of driving innovative concepts themselves: "So, if you talk about our subjects, our skill sets are driven by our employers" (I-9-006). Furthermore, it seems that operational participants expect industrial education to provide a cutting-edge learning experience that is tailored to each individual student (I-16-010; I-17-008), but this expectation might conflict with both their instructors and their employers.

Finally, instead of centering user acceptance, the development of technology is expected to be **problem-driven** and is following the principle of **economic action**: the benefits gathered by developing and deploying an OAS should outweigh its respective investment (I-3-017; I-5-011; I-14-002): "You can implement a project and I've now saved myself five seconds of process. What are you doing with that five seconds? Are you sitting there for five seconds with your hands in your pockets, doing nothing? Then, the improvement is really it's not even worth the paper it's written on. Or are you doing something of value adding with that five seconds" (I-13-025). Nonetheless, participants often express that digitization projects fail to realize a quantifiable benefit that compensates previous investments (I-13-025; I-1-020). Despite ongoing efforts in the development of OAS, participants expressed that there a very few cases or best practises that can be considered beneficial from an economical perspective (I-1-020; I-4-013). Therefore, this issue was characterized as **cost-benefit and effectuation challenge**: "The best practice cases are, in my opinion, quite rare and in some cases, it doesn't always seem to bring the benefits, if we're thinking about investment and cost benefits, that it claims it would foster" (I-1-020).

4.10. Broader context

The issue of yet unknown effects on long-term occupational health and safety can be seen as a major concern brought up by participants. Especially in the context of wearable technologies, participants criticize the absence of comprehensive medical studies that evaluate the effects of technologies on the human body. For example, leveraging smart glasses in order to support operator's daily picking process in logistics might have **negative side effects** on the eyes as well as the brain. Moreover, the utilization of data glasses also seems questionable with regard to ergonomic aspects and psychological stress (I-5-013; I-6-008; I-4-007; I-2-010; I-20-006).

Recent developments in digital technologies and robotics also bring up possible **social implications** of the respective technology. Participants anticipate that there might be a certain "gap between workers who are able to run the whole system, the whole production line, and the ones that simply fulfil tasks" (I-1-003). In other words, it appears to be questionable if operators whose jobs become replaced by autonomous systems will have the abilities to perform maintenance or programming tasks for those systems (e.g., I-5-013). Moreover, participants emphasize the need to be aware of the heterogeneity of workers, so it is important to develop OAS that are designed for different cultural and socio-economic subgroups (e.g., I-5-014). During the data collection process in study 2 and 3, it appeared partly as if the topic of OAS directly resonates with a subtle concern of becoming self-redundant on shop floors in the foreseeable future (cf. I-11-019; I-12-003; I-16-004): "I suppose in the future, you could get to a stage in which everything is fully automated. I don't think that would be a very prosperous future for us, I think would be shooting ourselves in the foot" (I16-004).

5. Discussion

This section discusses the implications of the contrasting stakeholder perspectives identified in Section 4. A key difference of stakeholder perspectives is in the anticipated level of automation and the degree of human-centricity on future shop floors. We also discuss the challenge of effectively integrating human-technology and reflect on limitations of this work as well as opportunities for future research. There is no particular focus on technological limitations and challenges, or human–machine interaction design within this paper, unless mentioned by stakeholders. However, some technological limitations and challenges are reviewed in Related Work (Section 2).

5.1. Implications of contrasting perspectives

Previous work has already expressed the need for modeling organizational, user, and operational contexts (Belkadi et al., 2020), as well as a need to consider operators' age distribution (Peruzzini & Pellicciari, 2017) when integrating technology-augmented work configurations. Further, encompassing different strategic, tactic, and operational roles of operators are expected to be of importance when designing intelligent manufacturing systems (Pacaux-Lemoine et al., 2017). Our study extends these contributions by highlighting that it is crucial to not only encompass the role of the operator, but also cross-hierarchical perspectives on OAS when modelling the industrial context. Our research shows that one of the most significant differences in perspectives appears to be the perception of the future of production systems, and the way humans and machines might work together in technology-augmented work configurations. In the literature, there appears to be a consensus that production should be *human-centric* (Pacaux-Lemoine et al., 2017; Romero et al., 2020; Kaasinen et al., 2020; Cimini, Pirola, Pinto, & Cavalieri, 2020). Further, any technology within an industrial system should be *subordinated* to humans (Bower, 2019). However, in industry the applicability of these assumptions above appear to decrease with the employees' proximity to the shop floor. While strategic participants appear to take on a human-centric perspective placing the human operator at the center of Industry 4.0, both tactic and operational participants seem to lean towards a technology-centric perspective (Fig. 3, Panel (a), Panel (b).

In the context of human-centric production, one lesson learned is the need for more efficient and transparent communication regarding the purpose of augmenting technology deployment in general. Although strategic participants already value human operators as an integral part of future production, this position needs to be communicated more explicitly throughout the organization to prevent misunderstandings, thereby supporting organizations in decreasing the fear of operators becoming redundant by the deployment of OAS. This, in turn, could improve operators' acceptance of OAS and innovation projects in the long term (Moencks et al., 2020).

As delineated in Fig. 3, Panel c), the expectations of the type of work that could be supported by OAS diverge as well. Strategic participants and many tactic participants anticipate OAS to support tasks that are cognitively challenging. However, in the context of OAS, operational participants tend to think of physical assistance or control mechanisms. Here, the associated risk of a misunderstanding between the stakeholders could also be reduced through participative assessment, co-development and deployment of technology-augmented work configurations. Therefore, before initiating projects related to OAS, not only should the general purpose of the technology be discussed with all stakeholders, but also the possibilities, benefits and the types of support that is intended to be developed (Moencks et al., 2021; Romero, Stahre, & Taisch, 2020).

Another potential area of conflict can be seen in industrial education

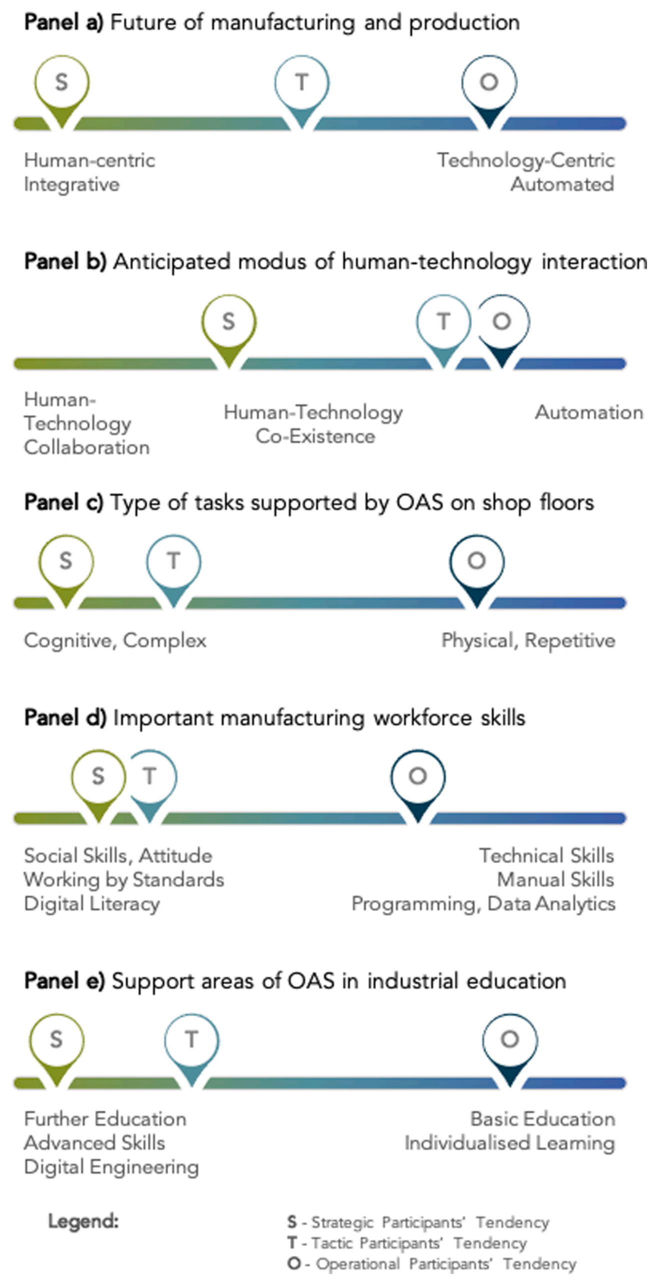

Fig. 3. Qualitative Visualization of Cross-Hierarchical Stakeholder Perspectives on OAS. Proximity of tendencies indicate the degree of alignment of strategic, tactic and operational participants on specific aspects of HTI.

(Fig. 3, Panel (d), and (e)). Tactic participants see the main purpose for industrial training in the acquisition of social skills. These skills are anticipated to be conveyed whilst interacting with peers, instructors, and supervisors. Further, basic manual manufacturing skills should be taught without involvement of OAS to convey an intuitive understanding for machining and materials. Many organizations do not seem to be willing to pay an additional fee to train their staff with technology-mediated learning tools. However, these factors seem to be largely unknown to operational participants. Instead, operational participants often emphasize the opportunities to enhance the efficiency of learning technical skills through the utilisation of OAS. Overall, the data therefore indicate that expectations management in companies regarding OAS and technology-mediated learning could be improved. This includes providing the specific reasons why a certain manufacturing skill could be augmented by OAS (or why not). Moreover, further research on the effects of individualized, technology-mediated learning might be needed for manufacturing organizations to evaluate the benefits of deploying or supporting OAS in industrial learning (Bower, 2019).

5.2. Application and effectuation challenge

The literature review revealed that digital engineering, data management and condition-based monitoring are expected to become major responsibilities of operators in future production systems (Siepmann & Graef, 2016). For example, digital twins or digital shadows allow organizations to map their current state of production facilities with ultra-low latency. In this context, related work often depicts the operator with configurable or supervisory control over the data streams on the shop floor (Bagheri, Zollanvari, & Nezhivenko, 2018). Further, established concepts such as the Industry 4.0 Maturity Index tend to focus on organizations' degree of interconnection between their sub-systems, the organization itself and the entire supply chain. Moreover, the index considers organizations' data-driven decision-making processes (Schuh, Anderl, Gausemeier, ten Hompel, & Wahlster, 2017). Correspondingly, the central paradigms of Industry 4.0 encompass data related macro perspectives such as vertical and horizontal integration (Siepmann & Graef, 2016).

Although it is stated that the operator is placed in the center of technological advances, there appears to be comparatively little focus on enhancing the execution of operational manufacturing tasks (Peruzzini & Pellicciari, 2017). Following this, an OAS would primarily aim to support operators in cognitive manufacturing tasks: for example, efficiently realizing a data-to-information conversion to improve operators' task execution.

It is often highlighted that technology-mediated learning is a complex and challenging endeavour (Bower, 2019; Erol et al., 2016; Lindberg, Seo, & Laine, 2016; Okano, Kaczmarzyk, & Gabrieli, 2018). It involves engineering innovative learning environments while simultaneously assessing their effectiveness' (Alavi & Leidner, 2001). Although both the reviewed literature and our qualitative study accentuate the benefits of technology-mediated learning, our results indicate that this topic appears to be controversial in industry. Especially in industrial education, instructors appear to place a lot of focus on teaching social skills, behaviors and attitudes whilst technology-mediated learning, on the other hand, primarily focuses on teaching technological knowledge. Moreover, participants anticipate the role of teaching in industrial education is continuing to be an integral part of manufacturing and production in the future. Learning practical activities within a simulation could potentially cause operators to lack an *intuitive feeling* for machining processes. Additionally, it is pointed out that industrial training follows the need of organizations that are running operations in respective industries. In other words, the deployment of technology-mediated learning might not be beneficial until it is fostering a set of skills that are explicitly needed by organizations. It thus remains unclear if OAS or technology-mediated learning can be considered effective tools for acquiring manual skills in industrial education environments.

Both the literature review and the qualitative study identified some case studies or prototypes related to OAS (cf. Section 2). While participants or related work often discuss the opportunities and chances of digitisation and OAS, we were not able to find evidence of realized benefits that could be quantified. In fact, participants stated that, due to disappointing results, many companies stopped their development of OAS as there apparently seems to be an issue with the effectuation of OAS in general.

Lastly it is noteworthy, that little focus was placed on technological feasibility by stakeholders. Yet, previous research has shown that despite off-the-shelf solutions for human-technology integration emerge on the market, immaturity of technology is still limiting adoption (Masood & Egger, 2019). This includes hardware readiness (Masood & Egger, 2019), or lacking suitable interfaces for human-automation interaction (Romero, Gaiardelli, Powell, Wuest, & Thürer, 2019). Here, future technology research is needed to ensure that contextual requirements identified within this paper, can actually be implemented in the future. Also, research should contribute to further educate industrial stakeholders on the technological state-of-the-art in human-technology integration to facilitate expectation management.

5.3. Limitations and future research

This work has strived to enrich understanding of cross-hierarchical perspectives on technology-augmented work configurations in the context of the operator 4.0 (Romero et al., 2020; Pacaux-Lemoine et al., 2017). The purpose of our work is not to claim a general validity in the manufacturing industry for specific positions of participants, but instead to enquire a possible context regarding OAS and areas where human abilities could be augmented. On an abstracted level, it can be expected that the controversies identified in this study may also result in controversial discussions in manufacturing organizations or industries. At the same time, we anticipate that elements which can be considered common ground in our study are also agreed upon in other organizations. However, these assumptions should not prevent companies or organizations from the process of verifying each aspect for their own case; our study might not give detailed answer on the actual skills that are most important to be augmented in a manufacturing organization. However, it provides an indication for the type of skill sets that could be useful to be augmented (e.g., cognitive support for exception handling), although the identification of the manufacturing skill which could be useful to be augmented has to be realized by the individual organization.

Although much care was taken to adopt a neutral, value-free and non-judging position, the findings of this study remain subject to the contextual and subjective biases of qualitative research.

6. Conclusions

We address an essential success factor of human-technology integration in industry: organizational factors (Masood & Egger, 2019; Pfeiffer, 2016; Cimini et al., 2020). There seems to be a consensus in the literature that the different strategic, tactic and operational roles of operators have to be considered when designing technology-augmented work configurations (Pacaux-Lemoine et al., 2017). However, the perspectives of strategic, tactic and operational operators on OAS are not yet fully understood (Moencks et al., 2020). Therefore, this work investigates how the different perspectives of stakeholder groups align with each other regarding the utilization and acceptance of technology-augmented work configurations. Our contribution is valuable as it provides HTI researchers with some guidance on aspects that can lead to challenges in the introduction of OAS. For example, executives and managers tend to have a different perspective on the degree of automation and robotization needed on future shop floors in comparison to employees assigned to tactical and operational levels of the organizational hierarchy.

One learning opportunity can be seen in the need for more efficient and transparent communication regarding the purpose of augmenting technology deployment and HTI in general. Although strategic participants already value operators as an integral part of future production, this position needs to be communicated more explicitly throughout the organization to prevent misunderstandings such as the fear of operators becoming redundant by the deployment of OAS. This, in turn, could improve operators' acceptance of OAS and innovation projects in the long-term view.

The paper's human-centric and technology neutral approach provides a more integrative orientation for organizations that strive to prioritize projects in future industrial research regarding human-centric production. Our study was carried out independently from a specific technology that could be assessed within a specific application area which, in turn, might provide organizations with a rather sociological perspective that can be compared with the perspective of engineers or developers that propose to introduce a certain OAS.

With regard to the technical skills required on shop floors, our findings emphasize the importance of working by standards, continuous improvement, exception handling, creative problem solving and data handling. Accordingly, major applications of OAS can be seen in (a) variety and exception handling; (b) support of standard operating procedures; (c) support in data analysis, diagnosis and optimization; and (d) technology-mediated learning, further education and digital engineering. Moreover, certain elements that could enhance acceptance of OAS were identified; among others, the elements include (a) the type of support; (b) the degree of machine involvement; and (c) the support initiation mechanism. Finally, it appears reasonably useful to strive for OAS that augment cognitive human abilities such as the data-to-information-to-knowledge conversion, rather than physical abilities in human-centric technology-augmented work configurations on future shop floors.

As for wider implications, this paper suggests that HTI researchers need to be mindful of the highly contextual stakeholder requirements whist developing and integration human-technology systems. It appears that industry practitioners consider organizational factors—such as the underlying context and stakeholder requirements—as the most important success factors of HTI in industry.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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