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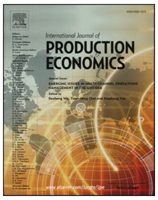

Industry 4.0 and the human factor – A systems framework and analysis methodology for successful development

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ABSTRACT

The fourth industrial revolution we currently witness changes the role of humans in operations systems. Although automation and assistance technologies are becoming more prevalent in production and logistics, there is consensus that humans will remain an essential part of operations systems. Nevertheless, human factors are still underrepresented in this research stream resulting in an important research and application gap. This article first exposes this gap by presenting the results of a focused content analysis of earlier research on Industry 4.0. To contribute to closing this gap, it then develops a conceptual framework that integrates several key concepts from the human factors engineering discipline that are important in the context of Industry 4.0 and that should thus be considered in future research in this area. The framework can be used in research and development to systematically consider human factors in Industry 4.0 designs and implementations. This enables the analysis of changing demands for humans in Industry 4.0 environments and contributes towards a successful digital transformation that avoid the pitfalls of innovation performed without attention to human factors. The paper concludes with highlighting future research directions on human factors in Industry 4.0 as well as managerial implications for successful applications in practice.

1. Introduction

The fourth industrial revolution, also termed Industry 4.0 (I4.0), has recently gained considerable attention in the production research domain (Lu, 2017; Xu et al., 2018; Liao et al., 2017). The aspiration behind I4.0 was to propose an industrialisation model suited to Germany's position as both a producer and user of high-technology production systems (Kagermann et al., 2013). Industrial revolutions are often framed in a technological perspective: the 1st industrial revolution relating to steam powered systems, the 2nd to the use of electrically powered systems, and the 3rd to the adoption of information technology and automation. Speaking broadly, I4.0 refers to the further digitalization and integration of information technologies including applications such as the internet of things (Lu, 2017), cloud-based systems (Lu, 2017), cobots (Bortolini et al., 2017), big data analytics (Wang et al., 2016), additive manufacturing (Hofmann and Rüsch, 2017), and cyber-physical systems (Xu et al., 2018). These systems enable a "smart factory" (Frank et al., 2019; Osterrieder et al., 2020), in which humans, machines and products communicate with each other via both physical and virtual means (Kagermann et al., 2013), and can contribute to increased sustainability (Bai et al., 2020). We point out the aspirational nature of I4.0; while previous industrial revolutions were identified and examined mainly after they had occurred, the conceptualisation of I4.0 and associated application of technologies is just beginning and is part of a deliberate industrialisation strategy.

Beside technological push-factors (Frank et al., 2019), I4.0 is also characterized by different pull-factors (Lasi et al., 2014) that contribute to a shift of paradigms. For example, individualized customer demands can be seen as a main driver of I4.0, since the fulfilment of individualized demands without an increase in costs (this is often referred to as 'mass customisation' or 'product individualisation') is one of the superordinate goals of using the different technologies (Winkelhaus and Grosse, 2020). However, it is still not fully clear to many in both industry and research what fully realised I4.0 applications might look like or how they might operate. For most practitioners, the digital transformation and its implications on operations processes remain a big black box. The

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transformation of production due to both technological and paradigmatic drivers leads to fundamental changes of organisations and processes (Matt et al., 2015) and finally also of human work (Neumann and Village, 2012; Kadir et al., 2019). Within this context, attention to human factors (HF) has been particularly sparse, despite the evident centrality of HF in four of the eight I4.0 developmental priorities (i.e. managing complex systems, safety and security, work organization and design, and training and professional development) laid out in the seminal I4.0-report by Kagermann et al. (2013). This centrality of human aspects, we will show, is not reflected in the I4.0 research to date.

I4.0 and technological change are rapidly transforming virtually all areas of human life, work, and interaction. These changes are acutely apparent in the way human work is organized and performed. Prominent examples include the usage of mobile devices for the augmentation of processes and support of workers, e.g. for maintenance or in order picking. Collaborative robots support assembly workers, exoskeletons empower production and logistics workers, and cloud-based software solutions for enterprises are emerging at a high pace (see, e.g. Osterrieder et al., 2020). These examples are just a few new forms of interaction between humans and I4.0 technologies within business' transformation that, however, highlight the various and novel interactions humans are confronted with.

First attempts to structure these interactions are made, for example, by Romero et al. (2016), Ruppert et al. (2018) and Fantini et al. (2020), where the operator is interpreted in different roles, depending on the technologies used. As described by Romero et al. (2016), augmented reality used by an operator leads to the "augmented operator", who is presumably capable of making more informed decisions when maintaining a machine, for instance. These works, however, still focus on technological possibilities for the worker without analysing their influences on HF demands and operator experience in depth. Moreover, the "Operator 4.0" as proposed by these works is merely analysed in isolation, without consideration of the organizational, processual, psychosocial, and technological environment of the humans in the system.

This article discusses how failure to attend to HF in previous industrial system generations has had negative consequences for individual employees, production organisations, and for society as a whole. We further show that there has also been a lack of attention to HF aspects in research and development in I4.0, and present and discuss a framework for the systematic consideration of HF in the design and evaluation of I4.0 technologies and technology-assisted workplaces. Addressing these aspects, this paper pursues two research objectives (*ROs*):

> *RO1*: To identify which HF aspects have been considered to what extent in the scientific literature on I4.0.
> *RO2*: To provide a framework that includes foundational theories of HF to support the incorporation of HF aspects into corporate I4.0-system development efforts.

The remainder of this paper is structured as follows. A content analysis of research dealing with I4.0 is performed in Section 2, which highlights the definite lack of considering HF in this research area. In Section 3, concepts of HF in engineering design are discussed that are relevant for understanding the role of HF for system performance. In Section 4, an analysis framework is derived based on the discussed concepts to highlight how HF can be considered systematically in I4.0 research and development. In addition, an example application of the framework to a typical I4.0 use case is presented. The framework's implications are discussed in light of the insights obtained from the content analysis and theory section, and limitations as well as future perspectives of HF in I4.0 for researchers and managers are outlined in Section 5. Fig. 1 illustrates the outline of the paper and the research steps.

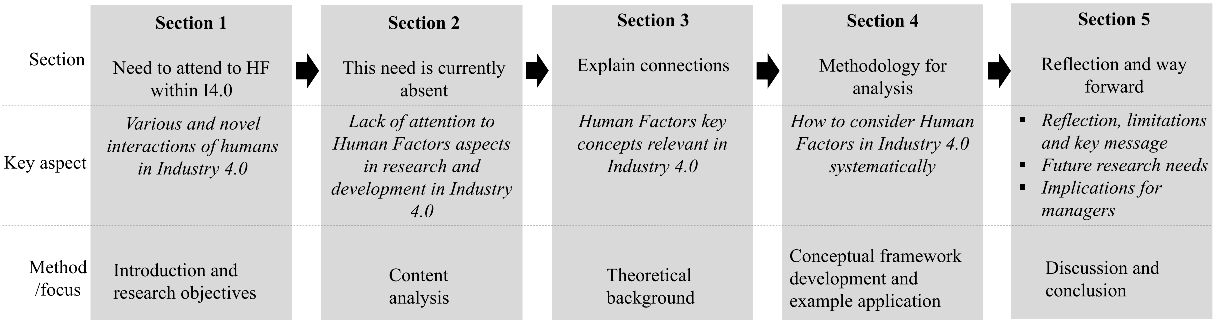
2. Evidence of lack of HF in I4.0 research: a content analysis

We present a content analysis of the literature on I4.0 in the next section to address RO1: examining which HF aspects have been included in the I4.0 literature up to now. We first briefly summarize previous related literature reviews. Subsequently, we outline the methodology and results of a content analysis of the literature on I4.0.

2.1. Insights from literature reviews and related industry 4.0 works

Two reviews focusing on HF-related issues in I4.0 could be identified. First, Badri et al. (2018) discussed occupational health and safety issues in the emergence of I4.0. In their systematic review, they identified eleven contributions as relevant, seven of these were conference articles. They concluded that "most articles are focused on new technologies driving this revolution and mentioned worker health and safety only briefly" (Badri et al., 2018). Second, Kadir et al. (2019) applied a broader search for contributions that do not only consider health and safety issues, but HF in general. Overall, 40 peer-reviewed articles were identified that use I4.0- and HF-related terms in the title, abstracts or list of keywords in Scopus, but again only 13 of these were journal articles. In a qualitative assessment of the identified articles, the authors pointed at mental, physical and organizational aspects considered, such as human-machine interaction or necessary IT skills as well as the possibility of automation of repetitive manual tasks. They concluded, however, that literature on this topic is still narrow and rare, and that more I4.0 research with deeper attention to HF is needed. Since these reviews generated their sample in 2018, we analyse these insights to exploratively update the outcomes. Based on this analysis, we noted that the term "Operator 4.0" has emerged as a research area of note during the last year. We provide a brief overview of this literature here.

Six recent journal articles could be identified dealing with the "Operator 4.0" concept that have not been included in the reviews of Kadir et al. (2019) and Badri et al. (2018) that are generally based on technology-driven approaches. One of these works is the one of Ruppert et al. (2018) that grounds a survey on technologies for the "Operator 4.0" based on the systematization of Romero et al. (2016). The focus is on IoT-based infrastructure instead of software-based applications like



	Section 1	Section 2	Section 3	Section 4	Section 5
Section	Need to attend to HF within I4.0	This need is currently absent	Explain connections	Methodology for analysis	Reflection and way forward
Key aspect	*Various and novel interactions of humans in Industry 4.0*	*Lack of attention to Human Factors aspects in research and development in Industry 4.0*	*Human Factors key concepts relevant in Industry 4.0*	*How to consider Human Factors in Industry 4.0 systematically*	▪ *Reflection, limitations and key message* ▪ *Future research needs* ▪ *Implications for managers*
Method /focus	Introduction and research objectives	Content analysis	Theoretical background	Conceptual framework development and example application	Discussion and conclusion

Fig. 1. Outline of the paper and interdependencies between sections.

big data. However, since the focus is on technologies, HF are only considered briefly although they are of great relevance for the applications.

Kaasinen et al. (2020) performed user studies in three companies focusing on "Operator 4.0" solutions. Each study used different outcome measures, such as increasing job satisfaction, performance or controllability of production, which are achieved by empowering and engaging the workers using I4.0 technologies, e.g. for knowledge sharing or personalized learning. In the case studies, also challenges were observed, including major doubts about technology usage raised by workers. Zolotová et al. (2020) performed laboratory case studies implementing different technologies. The authors concluded that using various technologies, for example for a "Smart Operator" or an "Analytical Operator", leads to better results compared to implementing only a single technology. Segura et al. (2020) mainly focused on visual computing technologies, especially augmented reality, but also virtual reality, cobots and social networks. In use cases, the authors showed how these technologies can facilitate decision-making processes of workers.

The last two articles are of a more conceptual character. Dealing specifically with cognitive automation as part of the "Operator 4.0" concept, Mattsson et al. (2020) provided a strategy answering the question of how cognitive automation systems should be designed for an optimal support of assembly workers. The authors developed a framework that could be used to reduce stress and improve complexity handling and transparency in cognitive automation. Lastly, Taylor et al. (2020) provided a different perspective on the "Operator 4.0" asking for chances of such a development for small, capital-constrained enterprises. Taking the economy of New Zealand as an example, they discussed whether there is a transition from an operator-role to a maker-role, since employees are more involved in designing products than in monitoring machines.

Overall, it can be seen that the explicit consideration of HF in I4.0-related research is scarce. The above-mentioned reviews focus on articles that explicitly deal with HF in I4.0 and did not find a large sample to draw their conclusions on. Moreover, even articles that deal with the "Operator 4.0" concept and its impacts on HF are only discussed in a few cases in depth. In most of the studies and also the original contribution of Romero et al. (2016), HF remain an afterthought and not a design objective, nor a means to achieve good designs. This is consistent with gaps in the industrialisation research identified by reviews in manufacturing (Neumann and Dul, 2010) and in warehouse systems research (Grosse et al., 2015; 2017). While I4.0 has been reviewed in terms of its impact on sustainability (Bai et al., 2020), the focus was so far on the external environment and not on the internal working environment (Docherty et al., 2002). The work of Bai et al. (2020) deals with the actual interaction of people and the system. These interactions will be crucial to the success or failure of a system design effort to achieve the functionalities proposed in that work. In contrast, the work of Pinzone et al. (2020) addresses social sustainability in cyber-physical production systems directly; it does so, however, from a high-level discussion of functionalities and does not address the specific issue of human-system interactions in the design and application of new technologies. Recognizing that there may be relevant discussions inside the body of papers that do not use HF terms in their title, keywords, or abstract, we conducted a content analysis of the body of available I4.0 literature to examine the extent of discussion of HF-related issues compared to purely technical ones.

2.2. Methodology

A content analysis (CA) is an established method to analyse published works systematically and to highlight the core of research as well as to identify research gaps (Spens and Kovács, 2006; Cullinane and Toy, 2000; Grosse et al., 2017). A CA is "a research technique for making replicable and valid inferences from texts or other meaningful matters to the context of their use" (Krippendorff, 2013). According to Neuendorf (2002), a CA enables the recognition of patterns in large data sets. The objective of the CA is to count specific keywords, called recording units (RU), in the sample, assuming that a high number of hits is an indicator for the importance of the keyword (Cullinane and Toy, 2000). We use the CA here as a method to compare the occurrence of use of key terms related to I4.0 and HF. The analysis at hand follows four steps: 1) material collection, 2) descriptive analysis, 3) category selection, and 4) material evaluation. We outline these steps in further detail in the following.

The sample consists of all papers containing the keyword "Industry 4.0" in the title, which guarantees a strong focus on I4.0 and a broad sample. The database Scopus was searched for articles, since it is among the largest, transdisciplinary databases for peer-reviewed journal articles, leading to 2650 results in the first step of the development of the sample. We then limited our search to peer-reviewed journal articles written in English, resulting in 646 hits. All sampled works were obtained as or converted into readable PDF documents to allow for the use of the text analysis software MAXQDA. To avoid biases, the reference lists of all papers were removed before starting the count of RU.

As can be seen in Fig. 2, the sample shows a steady increase of research interest from the first paper on I4.0 published in 2014 until its current climax in 2019. We observed an interdisciplinary character of the sample with regard to journals, which stresses the complexity of research in the emerging digital transformation of work.

In the next step, all articles were coded using the method of manifest coding (Babbie, 2013). For the analysis, we chose both a deductive and an inductive approach. In the deductive approach, three categories (I-III) including various *subcategories* for I4.0 and HF aspects were derived based on the theoretical insights presented in Sections 2.1 and 3.

I. Beginning with I4.0 concepts, there are three subcategories of relevance: First, I4.0 systems are based on the implementation of a wide range of different *technologies*, like IoT, CPS and Big Data. Second, there is a *paradigmatic change*, which leads to new targets of the actions performed. Third, a subcategory *I4.0 characteristics* is added, considering terms like "smart" or "collaborative" which could be seen as a mediator including terms that do not name a certain technology, but instead a certain characteristic of it that is necessary for target achievement.

II. With regard to HF, four subcategories were derived especially based on the perception-cognition-motor action-cycle and the demand-control-model (see Key Concepts 3 and 4 in Section 3.3). The *perception* of a given situation leads to the *cognitive processing* and, in accordance with memory interaction, to the decision to perform a *motor action.* This loops back to the situation, which is perceived again. Besides these, also *psychosocial aspects* influence the work environment for humans.

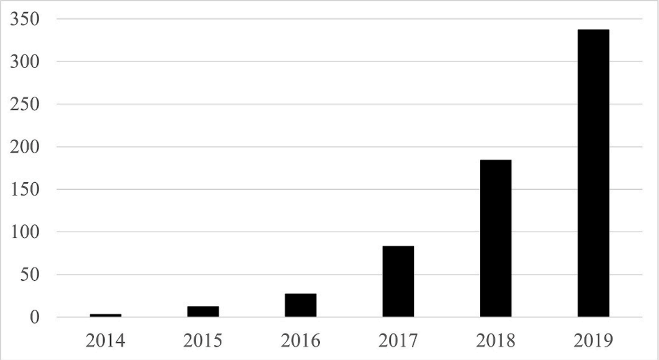


Fig. 2. Distribution of articles over time.

III. The third category "General HF terms" includes two subcategories. The first generally refers to human capabilities or load without referring to a certain system. These keywords are summarized in the subcategory *general terms.* The second deals with different and changing *roles of humans* in I4.0, e.g. from an operator role to a machine supervisor role.

Table 1 summarizes the three categories, related subcategories, and RU. Overall, we consider three categories (General HF terms, HF, and I4.0) and nine subcategories. For every subcategory, RU were derived deductively based on the theoretical background (Section 3). Different spellings (AE/BE), common abbreviations and different word endings (singular/plural) were considered in finalizing the list of RU. This deductive approach was complemented by an inductive refinement, where an entire coding process of all abstracts of sampled papers was performed, counting all words, abbreviations and symbols in the abstracts. The resulting list was then evaluated carefully to inductively refine the category system and RU. This approach ensured that all important RU are contained in the category system.

To account for possible biases, a sensitivity analysis was carried out, in which both the top ranked RU as well as the top contributing articles were analysed. The results of this analysis show whether only a few RU or a few articles contribute disproportionately to the result of a RU or category. Hence, it is possible to qualitatively account for correction factors (Abedinnia et al., 2017; Grosse et al., 2017).

Table 1
Category system and recording units.

Category & *Subcategory*	Recording Unit (RU)
General HF Terms	
Roles of Humans	customer, maintenance, user, human/s, employee/s, operator/s, worker/s, manager/s, expert/s, partner/s/ partnership, researcher/s, engineer/s, consumer, leader, stakeholder, workforce, staff, practitioner/s, personnel, supervisor/s, technician, employer/s, entrepreneur/s, instructor, programmer, shareholder, politician, co(−) worker, assembler, order picker
General Terms	work, social, risk, decision(−)making, labo(u)r, society, health, human resource/HR, attention, age/ing, effort, workload, human factor/s, assisted/assistive, socio-technical, work organization, ethics, OHS
Human Factors	
Mental	learn, knowledge, training, capabilities, skill/s, experience/s, education, behavio(u)r/al, teach/ing, cognitive/cognition, talent, competencies, hmi, human-machine, mental, qualification, creativity, psychology/psychological, human-centered, confusion/ing/ed, human-robot, e-learning, human-computer, forget/ting, human-technology, memory, reasoning
Physical	physical, safety, manual, ergonomic/s, fatigue/fatiguing, posture, well-being, gesture, musculoskeletal disorder
Psychosocial	involve*, culture/cultural, feedback, motivation, stress/ful/ing, teamwork, fairness, work design, psychosocial, job satisfaction, job demand, job control, support
Perceptual	read/ing, perception/ual, information processing
Industry 4.0	
Technologies	data, Industry 4.0, technology/technologies, information, machine, network/s, IoT/Internet of Things/Industrial Internet/iiot, sensor, digital/ly, automation/automated/ automatic, CPS/cyber-physical, cloud, robot, virtual/VR, big data, equipment, IT, simulation, digitiz(s)ation/digitaliz(s) ation, mobile, augmented/AR, wireless, autonomous/ autonomy, artificial/AI, rfid, ICT, blockchain, additive, digital twin, 3D printing, wearable, agv, cobot, gamification
Characteristics	smart, environment/al, flexible/flexibility, real-time, intelligent, integrated, predictive/prediction, complexity, lean, embedded, collaborative, robust/ness, data-driven, disruptive, ubiquitous, transparent, cooperative, visible, as a service, self-learning
Paradigm and Targets	performance, sustainability/sustainable, quality, energy, individual, industrial revolution, optimiz(s)ation, productivity, paradigm, customiz(s)ation/customiz(s)ed, privacy, transparency, trust, virtual/virtualiz(s)ed/virtualiz (s)ation, visibility, compliance, resilience, servitization, personaliz(s)ation, cyber security, usability, predictability

2.3. Results

Comparing the hits for the two most prominent RU in I4.0 and HF, the results of the CA reveal a strong disparity between both categories, as illustrated in Fig. 3. In fact, we noticed 29,591 accumulated hits for "Industry 4.0" and "Internet of Things" versus only 254 accumulated hits for "Ergonomics" and "Human Factors".

Table 2 summarizes the number of accumulated hits for the RU (#) in each subcategory. % indicates the percentage share of each subcategory (in terms of total number of hits of RU), and R shows the corresponding rank. Moreover, considering the different amount of RU per category, the mean # per RU for each category is calculated and the corresponding rank is given to ease comparability.

As can be seen in Table 2, 69% of all RU hits are observed in the category I4.0, with the subcategory *technologies* accounting for 50% alone (although the number of RU presents only 19%), which points to a high relevance this subcategory enjoyed in the sampled papers compared to all HF subcategories together. Also the relative ranks (mean hits per word) are led by all three I4.0-related subcategories. Within the I4.0 category, the RU counting the most hits are general terms like 'data' or 'Industry 4.0' that are followed by primary technologies like 'IoT'. On the characteristics side, 'smart', 'flexible' and 'real-time' are top ranked, and targets focus on 'performance', 'sustainability' and 'quality', but also 'individualisation' and 'customisation'. Lastly, there are some terms that were not found at all in the sample like "musculoskeletal disorder", "job demand", "job control" or "order picker", or only a few times as in the case of "job satisfaction" (14 hits), "psychosocial" (3 hits) or "work design" (11 hits).

The accumulated hits per subcategory are displayed in Fig. 4. As can be seen, in the four HF subcategories, there are two bars displayed, showing the results for all RU in the subcategory as shown in Table 2 in dark grey, whereas the light grey ones belong to the subsequently discussed sensitivity analysis.

2.4. Sensitivity analysis

Generally, the results of a CA should be reflected in light of possible

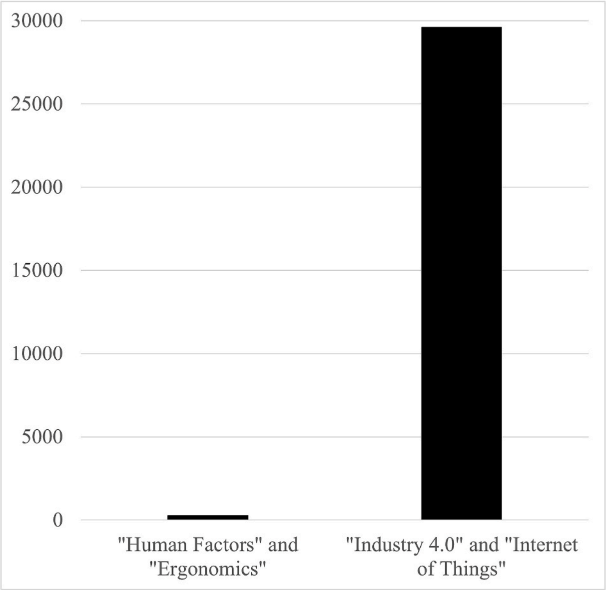


Fig. 3. Number of recording units for I4.0 and HF.

Table 2
Results of the CA category system.

Text only			Words in Category		—		
#	%	R	Nr. of RU	mean # per RU	R	*Subcategory*	Category
30563	11	2	30	1019	4	*Roles*	**General HF**
16457	6	6	18	914	5	*General Terms*	**Terms**
22372	8	5	27	829	6	*Mental*	**HF**
7060	2	8	9	784	7	*Physical*	
9693	3	7	13	746	8	*Psychosocial*	
978	1	9	3	326	9	*Perceptual*	
145767	50	1	34	4287	1	*Technologies*	**I4.0**
29564	10	3	20	1478	2	*Characteristics*	
27385	9	4	22	1245	3	*Targets*	

biases or influential points originating from some RU that can have ambivalent interpretations (Grosse et al., 2017). In our case, a more precise look at the hits in the HF categories is warranted. For example, “learning”, which is a very important HF term (Glock et al., 2019), is increasingly transferred to the I4.0 domain, for example in terms like machine learning, learning algorithms and artificial intelligence. Other critical RU in this regard are “behaviour”, referred to as systems behaviour, “read/ing”, which often refers to tag readings of RFID-based systems, or “feedback”, which is often used in a technical “feedback loop” context. Most of these RU are among the top three in the HF categories; acknowledging their possible relation to I4.0 technologies, the problem stated above becomes even more apparent. We identified six RU as critical in terms of ambiguous interpretations both in I4.0 and HF (shown in Table 3), and eliminated these from the analysis. The results change as illustrated in Fig. 4 (light grey bars in the HF subcategories). As can be seen, especially the subcategory *mental* HF as well as *perceptual* HF decline in their importance. The lack of attention to HF in I4.0 research becomes even more apparent.

Besides possible biases caused by RU, articles using a certain RU quite frequently could have biased the results. Therefore, we identified the top ten articles (out of the sample of 646 articles) that contribute most hits for RU in the HF category without considering articles that have been coded incorrectly in the HF category due to the above discussed ambiguous meanings of RU. Having a more precise look on them helps to interpret additional possible biases due to an overestimation of RU. The results are given in Table 4.

All articles focus on how to teach, learn and develop knowledge and capabilities for a future I4.0 environment, but only a few investigate the inherent changes induced by I4.0 for workers and especially for shop floor workers. Following, within the most contributing articles, the focus is not on how to design or interact with an I4.0 system. Based on this analysis, we conclude that there is an even more tremendous neglect of HF in I4.0 as suggested in the accumulated results, because these ten articles are responsible for about 8% of the hits in the HF categories, whereas they only account for about 1.5% of the sample. This is due to an extreme distortion of the mental HF category where only a few articles account for many hits and the different meanings of HF keywords bias the results, too.

We can now conclude on the first research objective, which focused on identifying which HF aspects have been considered to what extent in the I4.0 literature: In the sample of research articles containing the term “Industry 4.0” in the title, we found a clear focus on technologies relevant for paradigmatic changes. The discussion of general HF terms such as roles, as revealed by the results of the CA, seems to indicate an awareness among researchers that their technological developments will influence people. The absence of specific HF terms suggests, however, that this technology focused research rather pays lip service to humans but does not deal in any substantial way with human-system interaction, which causes the concerns that researchers are not paying attention to human aspects in their development work. When considered, then mental HF followed by physical HF have tended to be more common considerations, whereas psychosocial and perceptual aspects have been widely neglected, which manifests a clear lack of HF in I4.0 research. This suggests the I4.0 research is “blind” to the nature of the human system interactions in the systems they are helping to design. This does not bode well for the success of I4.0 approaches, or for the people forced to endure them. To contribute to closing this gap, we develop a framework for the systematic consideration and analysis of HF in the design and evaluation of I4.0 systems in the following sections.

Table 3
Recording units with possible ambiguous interpretations.

HF Recording Units	*Subcategory*	Industry 4.0 context
learn/ing	*mental*	e.g. learning algorithms, machine learning
training	*mental*	e.g. training an algorithm/a machine
behavio(u)r/al	*mental*	e.g. system behaviour
feedback	*psychosocial*	e.g. feedback loops
read/ing	*perceptual*	e.g. RFID-/tag-reading
memory	*perceptual*	e.g. computer memory

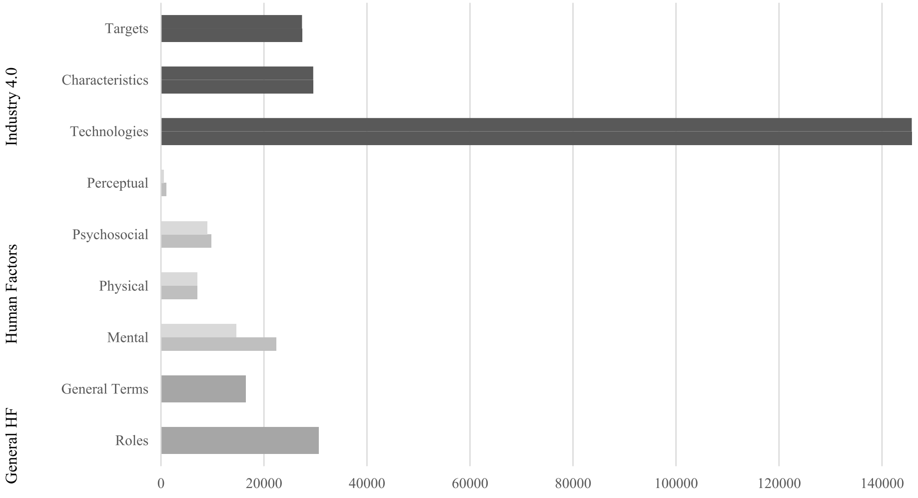


Fig. 4. Accumulated hits of recording units per subcategory in full texts.

Table 4
Most contributing articles in the HF category.

Paper	Content	*Subcategory* (Main RU)	Number of hits top RU/ all HF RU
Maisiri et al. (2019)	Performs a systematic literature review about technical and non-technical skill requirements for engineers in I4.0 and how to develop them	*Mental* (skill)	236/380
Shamim et al. (2017)	Conceptualizes management practices for I4.0-analogue developments in the hospitality sector including HF influences	*Mental* (knowledge)	131/351
Longo et al. (2019)	Proposes a solution for training of staff for emergencies in industrial plants using I4.0-technologies	*Mental* (training)	181/344
Chong et al. (2018)	Investigates the impacts of I4.0-technologies and 3D printing for teaching engineering programs	*Mental* (teach)	80/337
Hariharasudan and Kot (2018)	Studies I4.0's influences on employee qualification focusing on the effects of Education 4.0 and Digital English	*Mental* (learn)	105/318
Chi (2019)	Investigates an application for English learning especially for engineering learners within Industry 4.0	*Mental* (learn)	90/303
Sackey et al. (2017)	Surveys learning factories for I4.0 education in industrial engineering programs	*Mental* (learn)	161/287
Stachová et al. (2019)	Analyses employee education for I4.0 focusing on external partnerships for personal development processes comparing different countries	*Mental* (knowledge)	89/279
Hang et al. (2018)	Surveys influences on training quality and student satisfaction in the context of I4.0 education programs	*Mental* (training)	148/276
Azmimurad and Osman (2019)	Analyses vocabulary learning strategies among students for the expanded vocabulary needs in engineering within Industry I4.0	*Mental* (learn)	185/273

3. HF in engineering design

3.1. HF and worker health

We adopt the definition of HF (synonymous with the term ergonomics) from the International Ergonomics Association as being "concerned with the understanding of interactions among humans and other elements of a system […] design in order to optimize human well-being and overall system performance" (IEA Council, 2019). The failure to address HF adequately in the design of work can lead to substantial problems. Current estimates from the International Labour Organisation place the annual work-related mortality at 2.78 Million deaths per year globally (ILO, 2019). This amounts to about one work-related death every 11.3 s. Musculoskeletal disorders (MSDs), such as repetitive strain injuries, are a global problem caused by the design of work – particularly due to high forces, high duration and repetition of efforts, poor working postures, and poor psychosocial work environments (NRC, 2001). Population studies indicate that 20% of the general population suffers from a work-related MSD (Major and Vézina, 2015). In some manufacturing sector studies, MSD rates among system operators approach 100% (NRC, 2001). These disorders are caused by the design of the work system - when the demands on the system operators exceed their tolerance (NRC, 2001; Neumann and Village, 2012). Failures to attend to HF in design have been identified throughout the design and operationalization process (Neumann et al., 2002, 2006; Kihlberg et al., 2005; Kolus et al., 2018). In short - these problems are caused by system designers. The costs for workplace injuries are enormous, estimated in the USA to be on par with the costs of all cancers combined (Bhattacharya and Leigh, 2011). While managers frequently look at direct compensation costs as an indicator of the MSD problem, the indirect costs are often much larger and can include hiring costs, training costs, reduced performance, increased errors, increased scrap costs, and wasted managerial effort among the many indirect costs aspects related to employees' MSDs in manufacturing (Rose et al., 2013). Efforts to model the costs associated with increased MSD risk factor exposure suggest that 2–8% of product costs may be caused by these risks (Sobhani et al., 2016). The problems caused by poor HF in system design warrants Kagerman et al.'s 4th priority regarding system safety. However, systematic reviews have revealed very little attention to safety issues in the I4.0 context to date (Badri et al., 2018).

3.2. HF and operations performance

While the negative consequences of poor HF in the design and implementation of production innovations are a serious concern, we note also that HF is an essential aspect of organisational profitability and can provide strategic advantages to companies (Dul and Neumann, 2009). Benefits from the application of HF include improvements to productivity, technology implementation, quality, and system reliability. Studies examining both human outcomes and system benefits from HF application generally find that the system gains are considerably greater than the financial cost avoidance from reduced compensation costs alone (Rose et al., 2013). System modelling studies revealed that substantial portions of production cost may be due to poor HF in the work system design (Sobhani et al., 2016). While production managers carry considerable tacit knowledge of the strategic advantages available from HF (Village et al., 2016), the quantitative financial benefits are often buried in financial systems and very difficult to isolate – they are 'hidden' in the accounting system (Rose et al., 2013). This has inhibited a broader understanding of the importance of HF amongst engineers and managers in operations settings (Broberg, 2007).

Accordingly, in particular the joint objective of performance and well-being are often seen as being in conflict, even though empirical research demonstrates the convergence of well-being and work system performance (Goggins et al., 2008). Besides performance and well-being, there is empirical evidence that considering HF in the design of operations systems also improves quality and reduces errors (Zare et al., 2016; Kolus et al., 2018). Indeed, people-forwards management practices are linked to competitive advantages that are, in the resource-based view of the firm, difficult to copy and that can be leveraged for longer periods than technology-only strategies which are easily replicated (Boudreau et al., 2003). However, despite the evidence that HF contribute to sustained competitive advantage, attention to humans is frequently separated from engineering design and management processes (e.g. Neumann and Village, 2012) and is also underrepresented in I4.0 research, as shown in Section 2.

3.3. Key concepts of HF

We propose five "Key Concepts" from the field of HF that can provide a basis for understanding the interrelation of I4.0 and HF. Key Concept 1 is the fundamental theoretical ground, namely the sociotechnical system theory. Following, a theory of HF in design is given as Key Concept 2, before the human-system-interaction cycle is discussed in Key Concept

3. Key Concept 4 focuses on psychosocial aspects and the demand-control model; an extension of Key Concept 3, and lastly Key Concept 5 gives insights into the theory of organizational drift to unsafe states.

Key Concept 1: *Industry 4.0 systems are sociotechnical systems.* In the sociotechnical system (STS) theoretic view, which is an outgrowth of general systems theory (Skyttner, 2001), all work systems are assumed to include social (human) and technical (machine) elements (for a history of STS, see Eijnatten et al., 1993). If there is a mismatch between worker capabilities and the demands placed on them by the system, then dysfunctional results, including errors and injuries, can be expected. This leads to a chain of negative consequences for both the worker and ultimately for the system as a whole. There are, we argue, no I4.0 systems that do not engage humans across the lifecycle in designing, installing, maintaining, operating, and dismantling (at end of life) these systems (Sgarbossa et al., 2020). Attention to the demands on the people performing these tasks is, therefore, a design requirement (Cherns, 1976; Clegg, 2000).

Key Concept 2: *Attention to HF must occur throughout design.* Fig. 5 illustrates the design process diagram showing key stages of the design process in which decisions affecting HF are made that have, firstly, (positive or negative) effects on humans in the system which, ultimately, affect system performance. In this view, the design of the product and the process as well as the management of the production system itself will determine the working environment for the employee. This, in turn, will have effects on the worker, which might be good, like gains in experience and motivation, or bad in terms of fatigue, pain and injuries. These worker effects then will have consequences for human performance, which will determine the overall system performance (Neumann and Village, 2012). If HF in system design and management are not appropriately considered, then poor system performance can be expected. This conceptual framework has been validated in case research in a variety of manufacturing contexts (Neumann et al., 2002, 2006; Sobhani et al., 2015). A recent review of HF-related quality problems in manufacturing identified HF-related quality risk factors in product design, process design, and workstation design stages (Kolus et al., 2018). From a design science perspective, we note that making changes to a given design gets more difficult and more expensive throughout the design process, becoming maximal once the system is operating and only retrofitting solutions are possible (Neumann and Village, 2012). Unfortunately, it is typical that HF are only deployed in these late, operational stages (Neumann and Village, 2012; Wells et al., 2012). The lowest cost and maximum opportunity - in essence the best cost-benefit results - come from considering HF from the earliest stages and then throughout the design project.

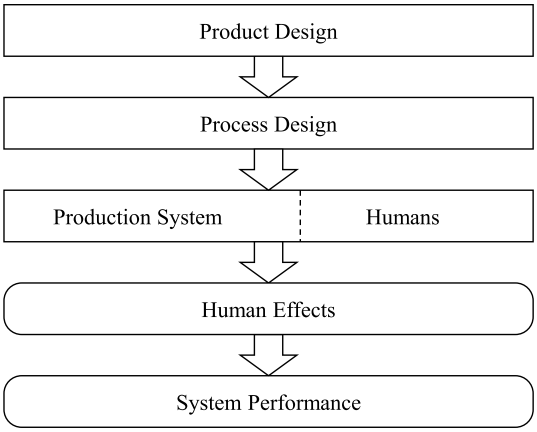


Fig. 5. Design process diagram (adapted from Neumann and Village, 2012).

Key Concept 3: *Human-system interaction engages perceptual, cognitive, and motor systems.* In the context of human-system interaction, the perception-cognition-motor action cycle is, we argue, always relevant (e.g. Helander, 2006). This model posits a continuous stream of interaction between the person and the system. In the first step, information about the machine is gathered via the sensory system including visual, tactile, olfactory, auditory, and vestibular systems – each with their own capacities and limitations that vary by individual. This sensory input is then processed cognitively – also with individual capacities and limits to memory and processing – into an understanding of the situation and planning for any desired action. This plan is then put into action via the musculoskeletal system – also with individual capacities and limitations. If this cycle is successful, the system will respond to the action providing (if it is well designed) new information to the sensory system allowing a new system state to be understood. Humans are continually engaged in this cycle of processing in an ongoing stream. From the design perspective then, it is crucial that sensory, cognitive, and musculoskeletal system capacities of individuals are not overloaded (or in some cases underloaded), and that the user has a robust understanding of the system allowing them to identify the correct actions required to bring the system to its desired state. For this reason, I4.0 system designers must ensure that the demands of their design are matched with human sensory, cognitive and motor capabilities, or they risk negative outcomes for the human or for the sociotechnical system as a whole.

Key Concept 4: *People have psychosocial needs.* Another critical aspect for successful sociotechnical system functioning is the psychosocial working environment – the perception of the social environment in the workplace. Critical dimensions here include job demands, job control, supervisory and co-worker support, and job satisfaction (for a more detailed discussion of psychosocial factors and their effect on physical and mental well-being, readers are referred to the review papers of Bongers et al., 1993 and Netterstrøm et al., 2008). In the foundational model of Karasek and Theorell (1990), employees experience mental "strain" when under working conditions that involve high work demands with a low sense of control. Under these working conditions, employees will experience significant and substantial increases in a broad range of mental illnesses and physical disorders. The empirical evidence here is substantial (Taouk et al., 2020; Letellier et al., 2018; Kerr et al., 2001; Moon and Sauter, 1996; Nieuwenhuijsen et al., 2010; Amiri and Behnezhad, 2020), and well developed survey tools, such as the Copenhagen psychosocial questionnaire (COPSOQ), exist to quantify these factors (Burr et al., 2019). There are few engineering studies examining how system design choices determine psychosocial conditions for employees, and how these ultimately affect system performance (e.g., Neumann et al., 2006). If, for example, I4.0 technologies are used to provide automated performance monitoring and enforcement of employees' working to a defined pace, then one might hypothesize that employee's sense of control and job autonomy at work will decline and the overall psychosocial profile will shift towards the 'high strain' states associated with negative outcomes.

Key Concept 5: *Organisations tend to "drift to unsafe states".* Rasmussen (1997) has pointed out that complex organisations engaged in process innovation and improvement will tend to "drift" to unsafe states. The rationale, supported by extensive analysis of organisational accidents, is that the efforts of many different actors working to minimise costs and optimize within their own limited domains will ultimately bring a complex system into an unstable state as they push the boundaries within their various domains in the pursuit of efficiency gains – leading to catastrophic systems failures (Rasmussen, 1997; Woo and Vicente, 2003; Burns and Vicente, 2000). If Rasmussen's assessment of dynamic organisations is correct – then the pursuit of I4.0 innovations is likely to follow this pattern as well: There will be unanticipated and unmanaged consequences emerging from the combined efforts of personnel in different parts of the system (Rasmussen, 2000). Emergent system characteristics can be particularly difficult to manage in design processes (Steiner et al., 1999; Burns and Vicente, 2000; Skyttner, 2001; Neumann et al., 2009). In a case study of the implementation of automated guided vehicles (AGVs), for example, unanticipated interaction between the AGVs and the layout of the workstation resulted in poor working postures and elevated pain levels in assembly operators (Neumann et al., 2006). The "drift to unsafe states" effect of Rasmussen (1997) helps explain why industrial revolutions, or fads like "Lean" (Näslund, 2008), have been seen as contributing to occupational injuries, accidents, and deaths. If I4.0 innovations are to try and break this pattern, then a systems approach to applying HF in design is needed (Neumann, 2017; Neumann and Village, 2012) - and researchers must develop better tools and approaches to support such system integration efforts. Isolated developments create unanticipated system risks.

The key HF concepts listed here pose both a challenge and an opportunity for I4.0 innovation. If HF is ignored, or dealt with in isolation, then underperforming systems and the ongoing problem of injured and killed workers can be expected. Deliberate and systematic attention to HF therefore poses an opportunity to break the pattern of previous industrial revolutions (see, e.g., Neumann et al. (2018)) examining the effects of a shift from craft to line production) and create better, more effective workplaces in the future. This, we will demonstrate next, is not happening yet, and therefore the vision of Kagermann et al. (2013) will not be achieved. The key concepts thus point to the need of multidisciplinary research and development that integrates technological and social foci in the design process – a classical problem in design (Kilker, 1999) and science (Snow, 1998). Hence, approaching I4.0 from a technology-driven perspective falls short of the systematic consideration of HF that is needed.

4. How to consider HF in I4.0 systematically

4.1. Framework and method development

Given the apparent inattention to humans in I4.0 research and development work, we propose a systematic framework for considering HF in the conceptualisation, design, and implementation of new technologies in operations systems. While we present this in the context of the current I4.0 trend, it is not specific to certain technologies. The framework is applied in five steps: 1) defining the technology; 2) identifying affected humans; 3) identifying task scenarios; 4) task analysis and impacts; and 5) outcome analysis. We describe each step briefly and then present an application example in the next section. A blank worksheet is provided in the appendix (Fig. A2).

Step 1: Defining the technology. This step is important as the framework operates, initially, as a thought experiment before more detailed testing approaches are chosen. The analysis may require knowledge of the physical form, assembly, use and maintenance tasks as well as possible failure modes for the system in question. Where these are unknown, the analyst would have to investigate alternatives and refine these projections as their development work proceeds. In addition, the characteristics of the technology should be known.

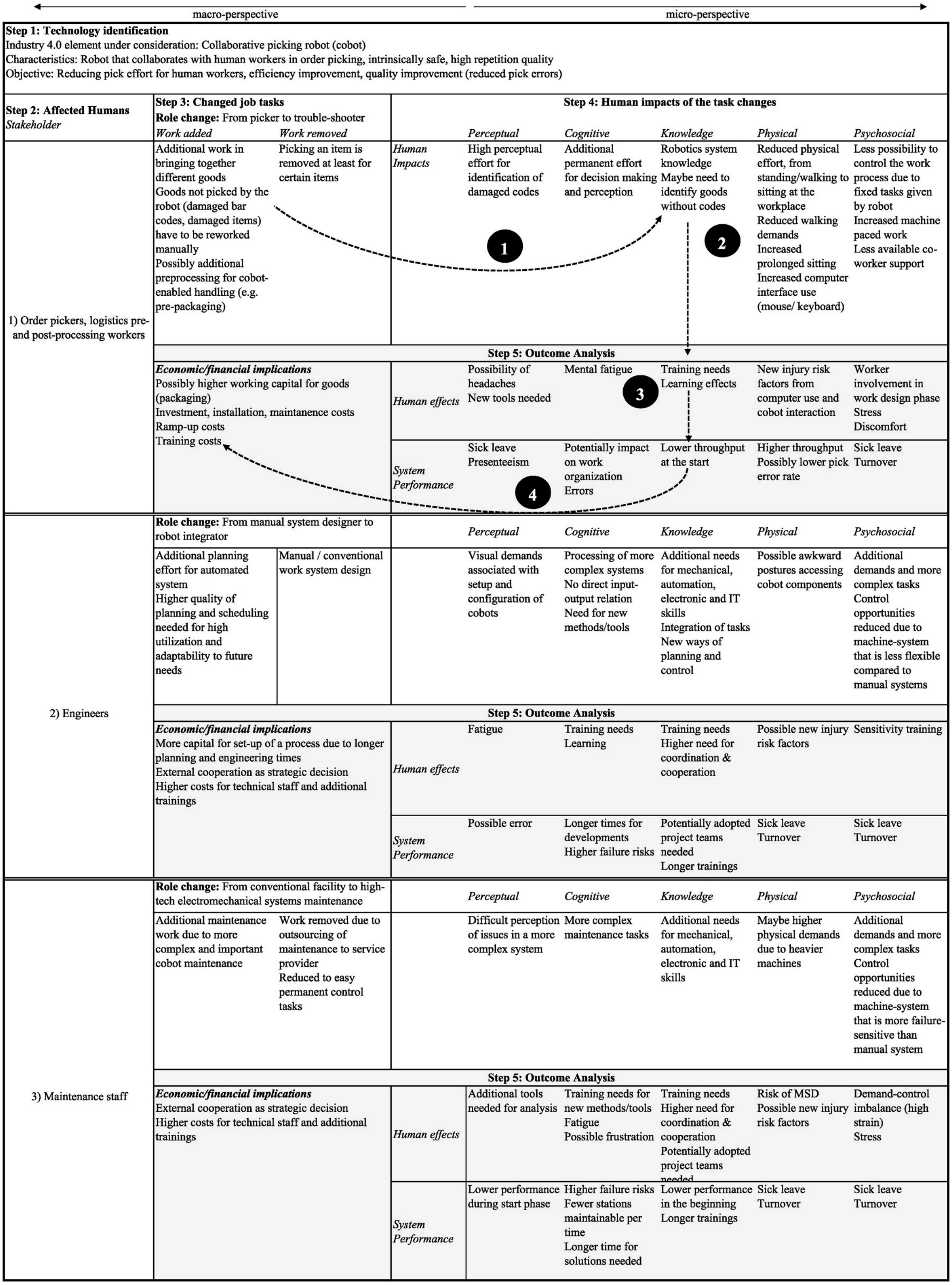
Step 2: Identifying the humans in the system. Following on Key Concept 1 - that all engineered systems are sociotechnical systems -, it is important to list the human roles that will interact with the design. A life-cycle perspective is important here and should include attention to stages of design, assembly, installation, operation, maintenance, and disassembly. There may be multiple scenarios for any one stage. For example, operations may include front-line workers in various scenarios, and also programmers or engineers engaged in operating the cyber-physical sociotechnical system. This list of stakeholders and human roles should be inclusive and as expansive as possible creating a set of "usage scenarios" (cf. Regnell et al., 1995) for considering the design. Forgetting a stakeholder group, such as maintenance personnel, means that their needs might be missed in system design, with possible negative consequences both for personnel and for long run system performance due, in this example, to increased maintenance costs. The idea of the human in the system can be very diverse. Each person entering the system will bring knowledge and will require new knowledge in order to operate effectively in the new sociotechnical system environment. As Key Concept 2 implies, attention to these stakeholders must be part of I4.0 development in the design stage, not an afterthought. While not every stakeholder of a company will be influenced by every I4.0 implementation, the influences might be more diverse than anticipated when cleaning staff, maintenance and engineering teams etc. are considered.

Step 3: Identifying task scenarios. For each usage scenario, the analyst must consider what tasks are being added to (e.g. more computer monitoring work) or removed from (e.g. paper work, or walking) each human in the system over the technologies life-cycle. How, in other words, will the persons' jobs change when they use this new technology, compared to the current scenario? Due to the design of tasks within these sociotechnical systems, the performance of the system as a whole will be influenced.

Step 4: Assessing the human impacts of the task changes. For each change in task identified in Step 3 - be it elimination of tasks or inclusion of new tasks - the analyst should assess the demands placed on the human in terms of perceptual, cognitive, and motor system demands (per Key Concept 3). In particular the implementation of new technologies and the related task changes are suggested to impact on the psychosocial stressors in the job (per Key Concept 4), in particular the effect on psychological job demands, the possibility of job control, role clarity, social support from co-workers and supervisors, and job satisfaction. Where these impacts are not understood, further investigation and evaluation may be required. By assessing these impacts, across all stakeholders, it becomes possible to identify more clearly the advantages and potential problems of adopting the proposed technology. In addition, it is important to consider the (new) knowledge needed to operate/use a certain technology.

Step 5 - Outcome analysis. In this final step the possible effects of the human impacts, identified in Step 4, on system performance should be considered. In particular, an analyst should consider the possible implications on employee time, on training needs, the probability of errors and hence quality, and on the health risks and wellbeing of the worker. If desired, the financial implications of these impacts could also be estimated (e.g., investments costs). An extra consideration in this step is the possibility of 'side effects' of the technology. For example, if a "smart scanner" must be strapped to the user's arm, there might be side effects associated with the comfort of straps and mass of the device when worn for 8 h. Another example for side effects of the use of I4.0 technology are headaches, which were reported when using augmented reality glasses (e.g. Wille et al., 2013). Therefore, the two sides of the framework can be considered as a macro-perspective and a micro-perspective. On the one side, especially the company's economic situation could be considered in the outcome analysis according to the work added and removed for every stakeholder. On the other side of the framework, the outcome analysis can especially be used for the micro-perspective, e.g. how to tackle challenges, new demands, secondary effects like negative outcomes of a used technology - although the context specificity of these costs make detailing this beyond the scope of this article and therefor a matter for further research.

As it is not possible to evaluate design and HF elements in isolation and expect safe performance without risking the drift to unsafe states (Key Concept 5), the proposed framework accounts for interaction of



Step 1: Technology identification
Industry 4.0 element under consideration: Collaborative picking robot (cobot)
Characteristics: Robot that collaborates with human workers in order picking, intrinsically safe, high repetition quality
Objective: Reducing pick effort for human workers, efficiency improvement, quality improvement (reduced pick errors)

Step 2: Affected Humans *Stakeholder*	**Step 3: Changed job tasks** **Role change:** From picker to trouble-shooter		**Step 4: Human impacts of the task changes**					
	Work added	*Work removed*		*Perceptual*	*Cognitive*	*Knowledge*	*Physical*	*Psychosocial*
1) Order pickers, logistics pre- and post-processing workers	Additional work in bringing together different goods Goods not picked by the robot (damaged bar codes, damaged items) have to be reworked manually Possibly additional preprocessing for cobot-enabled handling (e.g. pre-packaging)	Picking an item is removed at least for certain items	*Human Impacts*	High perceptual effort for identification of damaged codes	Additional permanent effort for decision making and perception	Robotics system knowledge Maybe need to identify goods without codes	Reduced physical effort, from standing/walking to sitting at the workplace Reduced walking demands Increased prolonged sitting Increased computer interface use (mouse/ keyboard)	Less possibility to control the work process due to fixed tasks given by robot Increased machine paced work Less available co-worker support
			Step 5: Outcome Analysis					
	Economic/financial implications Possibly higher working capital for goods (packaging) Investment, installation, maintenance costs Ramp-up costs Training costs		*Human effects*	Possibility of headaches New tools needed	Mental fatigue	Training needs Learning effects	New injury risk factors from computer use and cobot interaction	Worker involvement in work design phase Stress Discomfort
			System Performance	Sick leave Presenteeism	Potentially impact on work organization Errors	Lower throughput at the start	Higher throughput Possibly lower pick error rate	Sick leave Turnover
2) Engineers	**Role change:** From manual system designer to robot integrator			*Perceptual*	*Cognitive*	*Knowledge*	*Physical*	*Psychosocial*
	Additional planning effort for automated system Higher quality of planning and scheduling needed for high utilization and adaptability to future needs	Manual / conventional work system design		Visual demands associated with setup and configuration of cobots	Processing of more complex systems No direct input-output relation Need for new methods/tools	Additional needs for mechanical, automation, electronic and IT skills Integration of tasks New ways of planning and control	Possible awkward postures accessing cobot components	Additional demands and more complex tasks Control opportunities reduced due to machine-system that is less flexible compared to manual systems
			Step 5: Outcome Analysis					
	Economic/financial implications More capital for set-up of a process due to longer planning and engineering times External cooperation as strategic decision Higher costs for technical staff and additional trainings		*Human effects*	Fatigue	Training needs Learning	Training needs Higher need for coordination & cooperation	Possible new injury risk factors	Sensitivity training
			System Performance	Possible error	Longer times for developments Higher failure risks	Potentially adopted project teams needed Longer trainings	Sick leave Turnover	Sick leave Turnover
3) Maintenance staff	**Role change:** From conventional facility to high-tech electromechanical systems maintenance			*Perceptual*	*Cognitive*	*Knowledge*	*Physical*	*Psychosocial*
	Additional maintenance work due to more complex and important cobot maintenance	Work removed due to outsourcing of maintenance to service provider Reduced to easy permanent control tasks		Difficult perception of issues in a more complex system	More complex maintenance tasks	Additional needs for mechanical, automation, electronic and IT skills	Maybe higher physical demands due to heavier machines	Additional demands and more complex tasks Control opportunities reduced due to machine-system that is more failure-sensitive than manual system
			Step 5: Outcome Analysis					
	Economic/financial implications External cooperation as strategic decision Higher costs for technical staff and additional trainings		*Human effects*	Additional tools needed for analysis	Training needs for new methods/tools Fatigue Possible frustration	Training needs Higher need for coordination & cooperation Potentially adopted project teams needed	Risk of MSD Possible new injury risk factors	Demand-control imbalance (high strain) Stress
			System Performance	Lower performance during start phase	Higher failure risks Fewer stations maintainable per time Longer time for solutions needed	Lower performance in the beginning Longer trainings	Sick leave Turnover	Sick leave Turnover

Fig. 6. Example method application for a picking cobot.

system elements. We note, however, that this is highly subjective. If a given user group is missed, if a task scenario is skipped, or if a task analysis is poorly thought out, then the quality of the overall analysis will be compromised. There are many different methods that could be used to evaluate the task loads on users, ranging from qualitative to quantitative, that are compatible with this framework. The flexibility of the framework may be a strength in terms of its ability to be used with a broad range of technological or administrative innovation scenarios. Hence, a comprehensive picture of the influences of an I4.0 element can serve as a basis for the specific design of a work system prior to implementation. Problems identified at this stage can be explored and addressed within the system design to avoid future dysfunctional side effects in the eventual I4.0 operations system. To better illustrate this, we provide an example analysis next.

4.2. Example method application for a cobot

We consider the example of a collaborative picking robot (cobot) introduced as a new I4.0 element in a warehouse (see, e.g., Coelho et al., 2018). The cobot could be used to support operations processes in a smart factory (e.g. in kit preparation or line feeding) or in a smart logistics system. While the framework can result in extensive analyses, an abridged example is summarized in Fig. 6 as an illustration of an approach to applying this analysis.

Step 1: Characteristics and objectives of the cobot use are listed. This could be that the robot is intrinsically safe or that it is highly reliable, so failures are reduced. The company's objective in using the cobot is to reduce the physical effort for the workers and to improve efficiency.

Step 2: Stakeholders and human roles are defined. Most affected by the cobot are order pickers working in the same warehouse area, but also workers in pre- and post-operations as the cobot integration might require a different preparation of goods (e.g. special barcodes or RFID tags). This also impacts supply chain partners. Considering the life-cycle perpective, at first, engineering staff is involved in designing and integrating the system and afterwards, maintenance personnel needs to maintain it. Furthermore, administration is also affected and could even be broken down further. The tasks at the end of life disposal of the cobot remains as a final issue to address.

Step 3: In the next step, possible added and removed work is analysed based on task scenarios. Applying the cobot for picking work removes this task from the human worker. On the other side, work is added for the human, such as troubleshooting in cases the cobot was not able to identify goods or malfunctioned in some other way. Maintenance and engineering roles change from a conventional order picking facility to supporting a fleet of high-tech electromechanical systems. The cobot needs to be integrated and maintained which adds new work for both of these groups. Role changes can be derived, e.g. from manual work system designer to robot integrator.

Step 4: In the next step of the analysis, the impacts of technology use on the humans in the system are described. The added and removed work is analysed and the impacts of the technology usage are described on the perceptual, cognitive, knowledge, physical and psychosocial level. By using a cobot, the logistics workplace is changed by transferring picking tasks from the worker to the robot, which reduces the loads to the musculoskeletal system associated with walking and material handling tasks, but increases times working with computer systems using input devices and reading screens (with physical, perceptual and cognitive task loads). The worker then only receives goods with damaged barcodes or even damaged goods that the cobot cannot process, leading to new different loads for the perceptual system and maybe also the cognitive system – e.g. when considering whether a good is still in accordance with the standards or whether it should be rejected. The psychosocial factors might be influenced due to less autonomy and control possibilities or higher pace at work. If for example an employee's performance hinges on the cobot performance, frustration and stress for the operator will ensue whenever the cobot malfunctions. The new robot system can then require technical knowledge and capabilities beyond the usual protocols, which could unintendedly increase the workload not only for front-line workers, but also induce new challenges for engineering and maintenance staff.

Step 5: In the last step of the analysis, the outcome analysis, the objectively described changes are evaluated in terms of possible performance impacts. Using the cobot can increase performance (e.g. throughput by adding a night shift) and can contribute to better service levels due to fewer pick errors. It requires, however, investment and installation costs. The company may be able to lay-off front-line employees but will need more maintenance and engineering staff to manage the cobot fleet. If the cobot needs prepackaged goods, the working capital might increase as well. Focusing on outcomes of the task and impact on the workers, higher perceptual demands (in co-working with the cobot) could cause headaches or require additional tools to avoid this. Increasing cognitive and knowledge demands might influence work organization to allow for job rotation or additional training. Changes of the musculoskeletal demands could lead to new ergonomics risks as back injuries due to material handling decrease while shoulder and wrist disorders may increase from the increase in computer workstation tasks. If the robots are poorly designed for maintenance access, then injuries to maintenance personnel may arise as they attempt to keep the cobot fleet operational.

Fig. 6 summarizes the cobot example. Here, we also highlight one possible chain of effects: Implementing a cobot adds work to human order pickers for the identification of goods with damaged barcodes. Therefore, the worker has additional knowledge needs (1). As a result to this human impact, training should be offered to provide the necessary background for process handling (2). Training needs of course relate to initial learning effects that lead to a lower throughput at the beginning of the implementation and thus lower the system performance (3). Lower system performance and additional training needs lastly also have financial impacts for ramp up and training provision resulting from the added or removed piece of work (4). Hence, this chain of effects directly relates to Key Concept 2 and verifies the need to consider HF early in design. To further illustrate the framework, a second application example from manufacturing is presented in the appendix (Fig. A1). These examples are, by necessity incomplete and are meant to illustrate the analysis approach that the framework fosters. Further development of this framework into a user-friendly method is still required.

5. Discussion and conclusion

5.1. Key concepts

The developed framework allows a systematic assessment of the impacts of I4.0 technology implementation on human workers and system performance. It is theoretically grounded on five HF key concepts: 1) I4.0 are sociotechnical systems that involve people; 2) the needs of people must be considered via system design; 3) people have perceptual, cognitive and motor capabilities and limitations; 4) people have psychosocial needs; and 5) complex systems often drift to unsafe states. While this list might be criticized as incomplete, it provides a parsimonious basis to explain both the need and the opportunity for considering HF in I4.0 development. The first four concepts are axiomatic in HF engineering. There are no engineered systems without humans. Humans cannot be re-engineered, so designs must be made to suit them. Humans have known characteristics that must be accommodated. These four concepts would require a "black swan" case to refute them - cases we doubt exist in practice.

The last concept, Rasmussen's claim of the tendency to drift to unsafe states, is perhaps more a cautionary observation than a "law". This principle, however, has been well illustrated in a number of disaster scenarios (Rasmussen, 1997; Woo and Vicente 2003). Rasmussen went on to describe a framework that could help analyse complex systems to isolate the mechanisms that lead to system failures (Rasmussen, 2000). In the case of industrial revolutions, we see similar evidence. The pattern of specific injuries of workers in particular jobs was first observed by Ramazzini (1700) at the start of the first industrial revolution as workers began to spend a substantial amount of time performing a limited range of tasks due to the increasingly fine division of labour noted by Adam Smith (1776). This mechanism is still at play in "modern" production systems today (Palmerud et al., 2012; Neumann et al., 2018). Similarly, case studies of automation have shown that, while work tasks (and jobs) were eliminated, some people, especially those working downstream from the robot, had increases in repetitive movements implying increased injury risk (Neumann et al., 2002). While the drift to unsafe states effect is not an inevitable pattern, it seems to occur frequently. Key Concept #5 warns us that I4.0 will also contribute to and extend the global problem of work-related ill health if HF is not included in design stages (Key Concept #2). HF can help I4.0 designers avoid the "innovation pitfall" (Neumann et al., 2018) in which failure to attend to secondary human effects compromises the benefits that designers and managers had counted on for their I4.0 innovation efforts.

The developed framework can assist researchers in finding new topics and systematically addressing these gaps, for example in "human-centered industrial engineering and management" (Sgarbossa et al., 2020). To name only a few examples, the framework could be used to contribute to the diversity agenda, as systematically managing and customising the HF demands can open the door for increased diversity in employee characteristics and hiring (e.g., older workforce or workers with disabilities). There is also a need for more research that can help design teams understand the psychosocial impacts of their design choices (e.g. the implementation of a specific I4.0 technology) on employees and, ultimately, system performance. Psychosocial stressors and their impact on work autonomy, motivation or job satisfaction in the context of I4.0 are still not fully understood and require further research. If new I4.0 systems increase demands on employees, and possibly apply stringent monitoring of task performance (Kaasinen et al., 2020), then the combination of demands and lack of control will increase psychosocial strain in employees which is associated with a wide range of health problems ranging from musculoskeletal disorders to fatal heart diseases (see, e.g., Bongers et al., 1993). The CA suggests that relatively little attention has been paid to these issues in I4.0 research.

5.2. Content analysis

The results of the CA highlighted the lack of attention to HF in current I.40 research which appears to have a strong focus on technology and only occasional attention of human-system interaction. This failure to attend to HF in I4.0 research has been observed in previous industrial system generations (e.g., Neumann and Dul, 2010; Grosse et al., 2017) and has had negative consequences for individual employees, production organisations, and for society as a whole. Although a CA is able to identify such patterns providing quantitative attention to specific keywords within a literature sample, it does not consider the actual content of the paper as might be done in a conventional literature review approach. We note that our analysis highlighted RU that have ambiguous meanings, for example a paper on "machine learning" yielded 260 hits for the HF "learning" category. The sensitivity analysis employed aimed at reducing such biases and increase the reliability of the results. This analysis only used papers with "Industry 4.0" in the title, which might exclude relevant papers. One example for this are the works on "Operator 4.0" (e.g., Romero et al., 2018), which are not included in the sample as I4.0 is not mentioned in the title in these works. However, a more precise look on current writings, as discussed in Section 3.1, highlights that these approaches see the worker rather as the "problem" that I4.0 attempts to "solve" by technological means. These articles, however, do not necessarily address the needs of the people in the system and the broader secondary impacts these technologies may have. We argue that designing a system and considering HF as an afterthought does not lead to an efficient and productive system. Instead of re-designing the human (as proposed by the "Operator 4.0" concept), we propose a "humane" sociotechnical system design approach prior to the I4.0 implementation that will result in systems better suited to people and less likely to be compromised by negative human effects of poor HF in design. Substantial research is still needed to see how the proposed framework and methodology can be applied in practice.

5.3. Application issues and managerial implications

The framework proposed here warrants discussion. We see the framework as a starting point and a "thinking shell" that can be applied as a tool, however without a fixed application approach. While it is comprehensive, the suggested approach (including the length and the way of organising it) is subjective and hinges on the knowledge and imagination of the user. To account for this limitation, a preliminary version of the framework was presented to researchers and managers working in the area of human factors, operations management, and Industry 4.0 in an expert workshop where the face validity and utility of the approach was affirmed.

While application studies are needed to identify practical, evidence-based advice for using the methodology, we suggest a top down, staged approach to the framework. Top level management can use the framework on a higher level for a first feasibility and profitability estimation. If the proposed innovation proceeds, the stakeholders involved in the elaboration process, who are closer to the final workplace, can be engaged in cross-functional teams for the more detailed analyses. The identification of specific stakeholders to consider in the analysis will be highly dependent on the organizational context and the innovation under consideration. One of the strengths of the proposed methodology is the use of a life-cycle perspective to help identify relevant roles and personnel to consider and engage. Participation of key stakeholders implicated in the proposed change is a way to both draw on their knowledge and secure their support for the innovation project (de Looze et al., 2003). While this would reduce the chances of the analyst missing a specific issue, it does not overcome problems of "unknown unknowns" in the analysis. Although the framework does not guarantee a holistic picture, it helps structuring the multiple directions and interactions of complex I4.0 elements and channels thoughts on the actual influences on HF in a robust way. Fig. 6 and Fig. A1 provided, for example, do not include specific action plan elements that would be required in a specific application.

The current framework is intended to help managers avoid HF-related pitfalls in their innovation processes. Further research work is still needed to understand what kind of support, or tools, might be needed to help managers and design teams do this in practice. To the extent that appropriate design-level virtual HF assessment tools exist, it may be possible to conduct quantitative and objective analyses of identified scenarios (Perez and Neumann, 2015). Virtual reality and digital human models (e.g. Case et al., 2016; Chaffin, 2008) can assess postural issues related to the physical layout of the workstation or to access repair points in the system. For other issues, such as identifying psychosocial strain issues, design tools are missing and making prospective assessments can be difficult. More participative and engaging development processes may be required to capture these issues. Further research, including case studies of innovation projects, is needed to develop this analysis approach to increase ease of use and to extend its capabilities. Financial analysis, for example, could be included by building on recent models that predict production costs based on employee risk level exposures (cf. Sobhani et al., 2015, 2016).

There are a number of organisational dimensions that are implicit in this framework that managers should consider. For example: who is being held responsible for what in the design of the new system? Will researchers take responsibility to attend to potentially harmful side effects in their research work? Are design teams being given the mandate and resources they need to examine the unanticipated costs associated with the new technologies? Differences in orientation of designers, as being either technically focussed or socially focussed, has been suggested to be a major source of conflict in design teams (Kilker, 1999). Engineering teams often lack knowledge and mandates to attend to human aspects in their design work (Broberg, 1997). Similarly, social issues have been suggested to have fallen off the agenda in management research (Walsh et al., 2003). Case study research has shown that design teams and managers need unambiguous targets and appreciate quantitative indicators as they develop their capacity to include HF aspects in production system design (Village et al., 2014; 2015). The dynamics required to achieve buy-in for HF in engineering design of I4.0 systems remains a research need. Given the range of technologies included in the I4.0 concept, and the variety of organisations looking to exploit these innovations, we doubt there will be a “single best way” to adopt and deploy the current framework. Identifying and testing useful approaches for a given context remains a research need.

Finally, the implications of this work are important for corporate strategy (Dul and Neumann, 2009). Managers should be aware that each technology will inevitably affect their people – and that people form a difficult to copy strategic advantage that their origination can leverage for competitive advantage (Barney et al., 2011). Attending to the needs of people in I4.0 system design can support these strategic objectives. Managers can ask themselves, for example: is this being used to make work easier? or to control people tightly? These issues have implications for both physical and psychosocial working conditions in the operations system. Managers and researchers should consider HF as a means, not a goal, to achieve performance and wellbeing. If new technologies are developed or implemented without attention to HF, systems will underperform yielding “phantom profits” (Rose et al., 2013; Neumann and Dul, 2010) and tend to drift into unsafe states. This implies costs to both society and the organisation as secondary effects compromise the technology investment leading managers towards the “innovation pitfall” (Neumann et al., 2018).

5.4. Key message

This article aimed at identifying which HF aspects have been considered to what extent in the scientific literature on I4.0 and at providing a systematic approach that supports corporate I4.0-system development. We show that, to date, current research on I4.0 technologies and implementation have broadly ignored the humans in the I4.0 system. The systematic consideration and attention to HF in the digital transformation of work can avoid negative consequences for individual employees, production organisations, and for society as a whole. With this contribution, researchers as well as practitioners have a systematic approach to incorporate HF in the ongoing transformation, ensuring their I4.0 investments do not fall into the “innovation pitfall”. Concluding, we strongly call for the systematic integration of HF in future I4.0 research and development, which can contribute to overcoming the challenges of the digital transformation of work, supporting a satisfied and motivated diverse workforce with expanding capabilities suited to working in the I4.0 environment.

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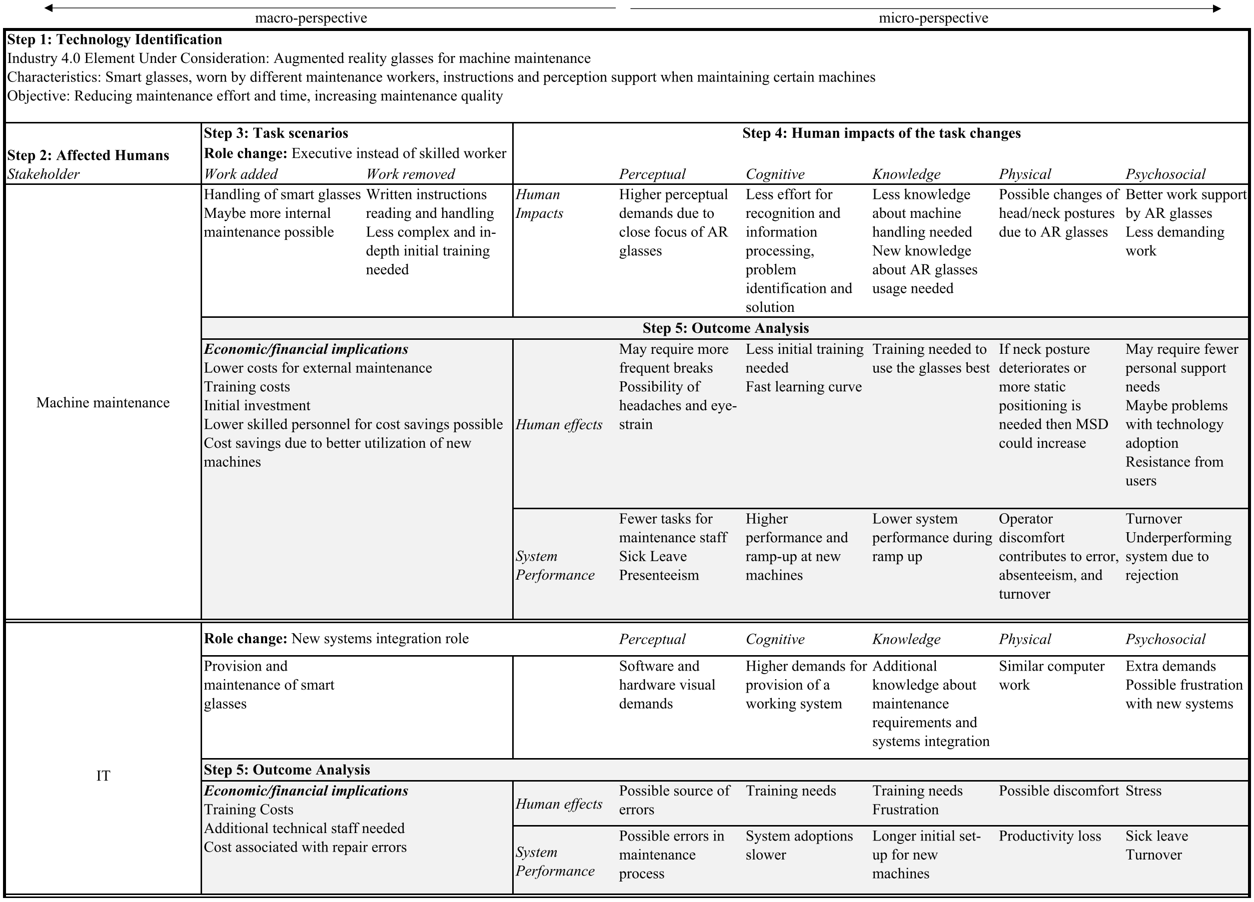
Appendix

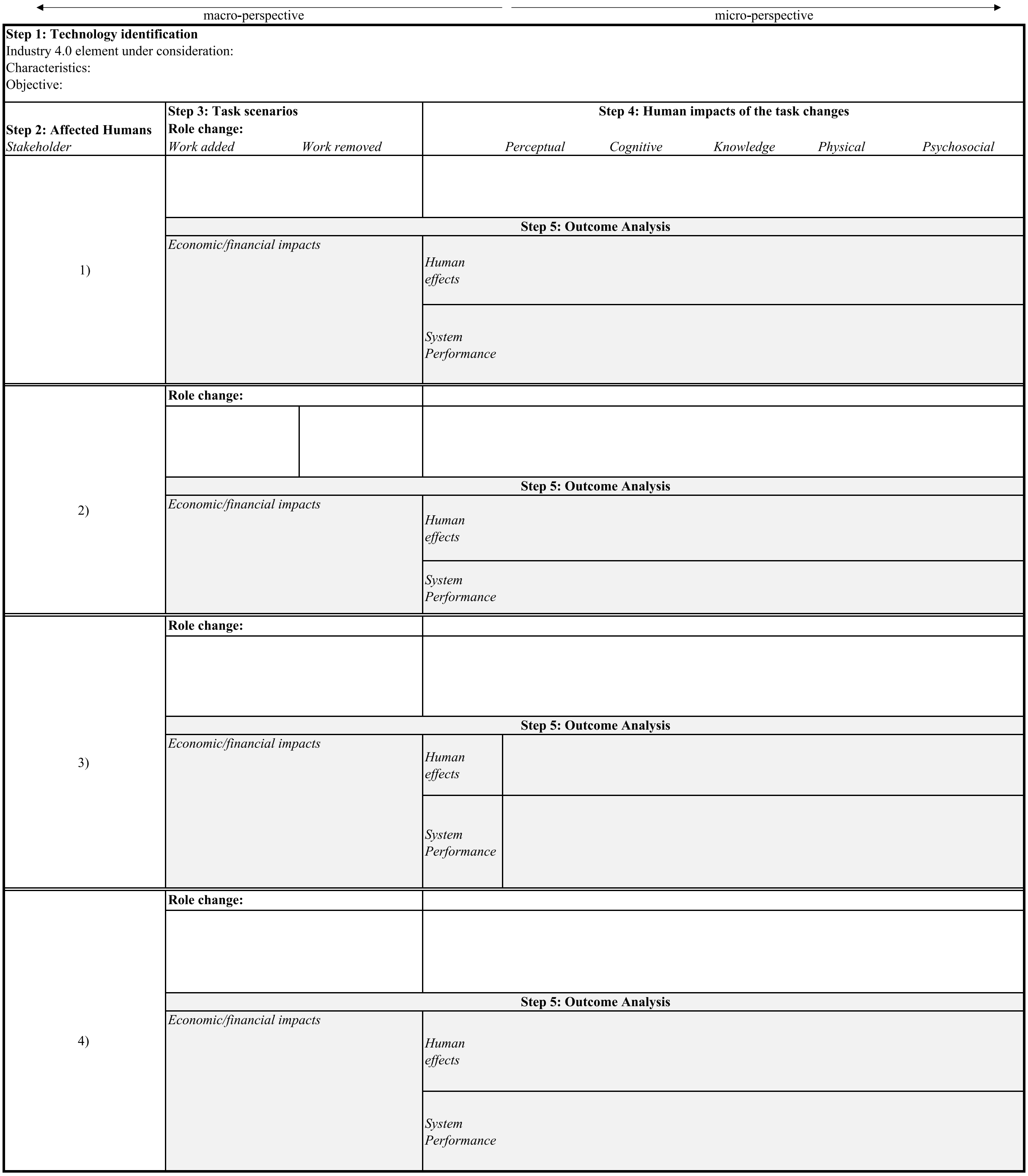
The appendix contains a second application of the framework exemplified at the implementation of augmented reality glasses for machine maintenance (Fig. A1) and a blank worksheet (Fig. A2).



Step 1: Technology Identification
Industry 4.0 Element Under Consideration: Augmented reality glasses for machine maintenance
Characteristics: Smart glasses, worn by different maintenance workers, instructions and perception support when maintaining certain machines
Objective: Reducing maintenance effort and time, increasing maintenance quality

Step 2: Affected Humans	**Step 3: Task scenarios**		**Step 4: Human impacts of the task changes**					
	Role change: Executive instead of skilled worker							
Stakeholder	*Work added*	*Work removed*		*Perceptual*	*Cognitive*	*Knowledge*	*Physical*	*Psychosocial*
Machine maintenance	Handling of smart glasses Maybe more internal maintenance possible	Written instructions reading and handling Less complex and in-depth initial training needed	*Human Impacts*	Higher perceptual demands due to close focus of AR glasses	Less effort for recognition and information processing, problem identification and solution	Less knowledge about machine handling needed New knowledge about AR glasses usage needed	Possible changes of head/neck postures due to AR glasses	Better work support by AR glasses Less demanding work
	Step 5: Outcome Analysis							
	Economic/financial implications Lower costs for external maintenance Training costs Initial investment Lower skilled personnel for cost savings possible Cost savings due to better utilization of new machines		*Human effects*	May require more frequent breaks Possibility of headaches and eye-strain	Less initial training needed Fast learning curve	Training needed to use the glasses best	If neck posture deteriorates or more static positioning is needed then MSD could increase	May require fewer personal support needs Maybe problems with technology adoption Resistance from users
			System Performance	Fewer tasks for maintenance staff Sick Leave Presenteeism	Higher performance and ramp-up at new machines	Lower system performance during ramp up	Operator discomfort contributes to error, absenteeism, and turnover	Turnover Underperforming system due to rejection
IT	**Role change:** New systems integration role			*Perceptual*	*Cognitive*	*Knowledge*	*Physical*	*Psychosocial*
	Provision and maintenance of smart glasses			Software and hardware visual demands	Higher demands for provision of a working system	Additional knowledge about maintenance requirements and systems integration	Similar computer work	Extra demands Possible frustration with new systems
	Step 5: Outcome Analysis							
	Economic/financial implications Training Costs Additional technical staff needed Cost associated with repair errors		*Human effects*	Possible source of errors	Training needs	Training needs Frustration	Possible discomfort	Stress
			System Performance	Possible errors in maintenance process	System adoptions slower	Longer initial set-up for new machines	Productivity loss	Sick leave Turnover

Fig. A1. Example method application for augmented reality glasses for machine maintenance.



macro-perspective ← → micro-perspective

Step 1: Technology identification
Industry 4.0 element under consideration:
Characteristics:
Objective:

Step 2: Affected Humans *Stakeholder*	**Step 3: Task scenarios** **Role change:** *Work added*	*Work removed*	**Step 4: Human impacts of the task changes** *Perceptual* *Cognitive* *Knowledge* *Physical* *Psychosocial*
1)			
	Step 5: Outcome Analysis		
	Economic/financial impacts		*Human effects*
			System Performance
2)	**Role change:**		
	Step 5: Outcome Analysis		
	Economic/financial impacts		*Human effects*
			System Performance
3)	**Role change:**		
	Step 5: Outcome Analysis		
	Economic/financial impacts		*Human effects*
			System Performance
4)	**Role change:**		
	Step 5: Outcome Analysis		
	Economic/financial impacts		*Human effects*
			System Performance

Fig. A2. Blank worksheet.

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