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Current Research and Future Perspectives on Human Factors and Ergonomics in Industry 4.0

Abstract

The journey toward Industry 4.0 and the increasing implementation of Cyber Physical Systems are evoking changes in human work and work organization, thus, creating new challenges and opportunities. To take advantage of these opportunities and deal with the challenges, we must gain a holistic understanding of the emerging socio-technical interactions and apply new human-centric approaches and methods when introducing new digital technologies and designing Industry 4.0-enabled work systems. In this paper, we present the findings of a systematic literature review, consisting of quantitative and qualitative data, focusing on investigating to what extent, what type, and how academic publications on Industry 4.0 integrate human factors and ergonomics in their research. Based on these findings, we point to future research needs, highlighting the need for further empirical evidence and improved collaboration between the academic fields of Industry 4.0, human factors, and ergonomics, as well as with practitioners.

Keywords

Industry 4.0, Cyber Physical Systems, Digitalization, Human Factors, Ergonomics, Literature review

1 Introduction

The final report of the Industrie 4.0 working group sponsored by the German Federal Ministry of Education and Research estimated that the changes introduced with Industry 4.0 will drastically transform work-content, processes, organization, and environments in the factories of the future (Kagermann, Wahlster, & Johannes, 2013). Kagermann et al. (2013) emphasized that work in Industry 4.0 will place greater demands on all members of the workforce in terms of problem-solving, abstraction, and managing complexity. Workers will also need to improve communication skills, become more independent, and take the responsibility of organizing their own tasks. These demands will have an increasing effect on the cognitive ergonomics of industrial work systems, thus, increasing the cognitive load of workers and changing the ratio between physical and cognitive load (Kong, 2019). However, Kagermann et al. (2013) suggested that these emerging changes will lead to benefits, such as greater job enrichment, more interesting working environments, and increased autonomy for the workers.

The catalyst behind these changes and the driving force of Industry 4.0, as well as the transformation of industrial production are new digital technologies, such as autonomous robots, augmented and virtual reality, the internet of things, additive manufacturing, and big data and analytics (Rüßmann et al., 2015). The implementation of these new digital technologies in manufacturing systems increase overall connectivity and bridge the gap between the physical and cyber computational space, resulting in the creation of Cyber Physical Systems (CPS) (Xu, Xu, & Li, 2018).

CPS are engineered systems that consist of humans and integrated computational and physical components, creating new levels of socio-technical interactions between humans, machines, materials, and objects (Wang, Törngren, & Onori, 2015). These new levels of socio-technical interaction between the physical and cyber space include complex interdependencies among organization, production, and control facilities (Zhong & Nof, 2015), which introduce various technical, organizational, and human-related changes (Becker & Stern, 2016).

The implementation and integration of such complex socio-technical systems call for a holistic understanding of the changes in the roles and responsibilities of workers and approaches for designing work, and work systems in Industry 4.0. To attain this holistic understanding, it is important to identify and document the appertaining challenges and opportunities related to human work. However, because the topic of Industry 4.0 is relatively new, research on human work in this context is still limited. Moreover, the available research within this narrow field is mostly focused on the integration of human workers into manufacturing processes at a lower operational level and neglects the upper levels, which deal with decision-making, control, and scheduling (Pacaux-Lemoine, Trentesaux, Zambrano Rey, & Millot, 2017). Thus, using a Human Factors and Ergonomics (HF/E) approach might be highly beneficial in terms of analyzing, understanding, and designing human work in Industry 4.0.

For decades, the field of HF/E has tested theories and developed tools, guidelines, and methods with the aim of ensuring the well-being of human workers. The International Ergonomics Association (IEA) defines HF/E as,

> the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design to optimize human well-being and overall system performance (IEA, 2018).

The IEA characterizes the field of HF/E into three domains of specialization: physical, cognitive, and organizational. Physical ergonomics focuses on the physical-elements, interactions, and activities. Cognitive ergonomics focuses on human mental processes and perception. Organizational ergonomics focuses on optimizing the surrounding organizational aspects of the system in which human workers operate. Table 1 shows an overview of the main domains of ergonomics and their content.

Table 1 – Overview of the main domains of ergonomics (IEA, 2018)

Physical Ergonomics	**Cognitive Ergonomics**	**Organizational Ergonomics**
Working postures	Perception	Organizational structures
Materials handling	Memory	Policies
Repetitive movements	Reasoning	Processes
Work-related musculoskeletal disorders	Motor response	Communication
	Mental workload	Crew resource management
Workplace layout	Decision-making	Work design
Safety and health	Skilled performance	Design of working times
	Human-computer interaction	Teamwork
	Human reliability	Participatory design
	Work stress	Community ergonomics
	Training	Cooperative work
		New work paradigms
		Virtual organizations
		Telework
		Quality management

Romero et al. (2016) suggest that the transformation into Industry 4.0 will require new design and engineering philosophies that are human-centric and focus on enhancing and augmenting the human's physical, sensorial, and cognitive capabilities, rather than unmanned autonomous factories. Using a human-centric approach to design Industry 4.0 work systems could improve the global performance of complex socio-technical systems and improve workers' well-being (Pacaux-Lemoine et al., 2017).

The aim of this paper is to investigate to what extent, what type of, and how academic publications on Industry 4.0 integrate HF/E in their research with the help of a systematic literature review; hereafter, pointing to future research needs, including better collaboration between HF/E and Industry 4.0 researchers as well as practitioners. Figure 1 illustrates the position of this paper in regard to research within HF/E and Industry 4.0.

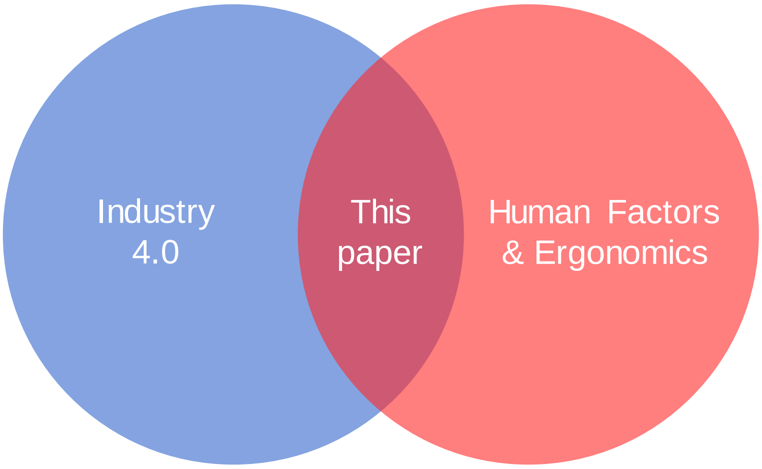

Figure 1 - The position of this paper in regard to research within HF/E and Industry 4.0

The organization of this paper is as follows: In Section 2, we describe the methodology and framework used to conduct the systematic literature review. In Section 3, we highlight the quantitative and qualitative results from the literature review and summarize the characteristics of HF/E research in Industry 4.0. In Section 4, we discuss the results and present a future perspective, as well as a research agenda for future research on HF/E in Industry 4.0. In Section 5, we highlight the limitations of this paper. In Section 6, we summarize the paper, provide final remarks, and draw a conclusion.

2 Methodology

To achieve the proposed aim of this paper, we conducted a systematic literature review. To answer the "what", we applied a quantitative data analysis approach focused on examining the extent of the overlap between the two academic research fields of Industry 4.0 and HF/E. This quantitative analysis included investigating characteristics of Industry 4.0 keywords associated with HF/E, the number of publications and publication types by year, types of data used in the publications, and publications in HF/E-related outlets. To answer the "how", we conducted a mix of qualitative and quantitative data analysis using the three broad HF/E domains characterized by IEA (2018) and highlighted in Table 1, as a coding framework for analyzing the results from the literature review.

2.1 Literature Search Strategy

To ensure the literature search was as extensive and inclusive as possible, yet within scope, the search strategy included combinations of several keywords that are relevant to HF/E in Industry 4.0. The scope of this paper is research on HF/E in Industry 4.0 in general, thus, the Industry 4.0 related keywords only included the broadest keywords used to describe closely related connotations similar to those mentioned and clustered by Liao, Deschamps, Loures, & Ramos (2017). In addition, due to the scope of this paper, the Industry 4.0 keywords did not include terms solely related to individual aspects of Industry 4.0 (e.g., Internet of Things, autonomous robots, big data, etc.).

In regard to the HF/E keywords, the keywords "human factors" and "ergonomics" are very broad and should capture most of the literature related to this research area. However, in accordance with recommendations of several experts within the HF/E research field, we added several other HF/E-related keywords. Table 2 shows an overview of the keywords used in the literature search. We did an individual search on each keyword(s) from Column 1 combined with each keyword(s) in Column 2 from Table 2, searching in titles, abstracts, and keywords using the electronic database, "Scopus."

Table 2 – Combination of keywords in the literature search

Industry 4.0-related keywords	HF/E-related keywords

Industry 4.0	Human factors
Cyber Physical System	Ergonomics
Smart manufacturing	Work system
Smart factory	Work design
	Work organization
	Well-being

When searching the database, we also took into consideration the different variations of spelling the words (e.g., *organization* and *organisation*, or *cyber-physical system* and *cyber physical system)*. The literature search only included academic literature i.e. peer-reviewed journal articles and conference proceedings published in English after the year 2013. The reason for not including papers prior to the year 2013 is that the origin of the term "Industry 4.0" is associated with Kagermann et al. (2013) and almost no other peer-reviewed journal articles or conference papers exist prior to that year.

2.2 Review Method

To ensure consistency and transparency throughout the entire review process, this study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), (Moher, Liberati, Tetzlaff, Altman, & Group, 2009) modified to fit with the review criteria specific to this paper. Figure 2 illustrates the PRISMA flowchart highlighting the various stages of the systematic literature review applied in this paper.

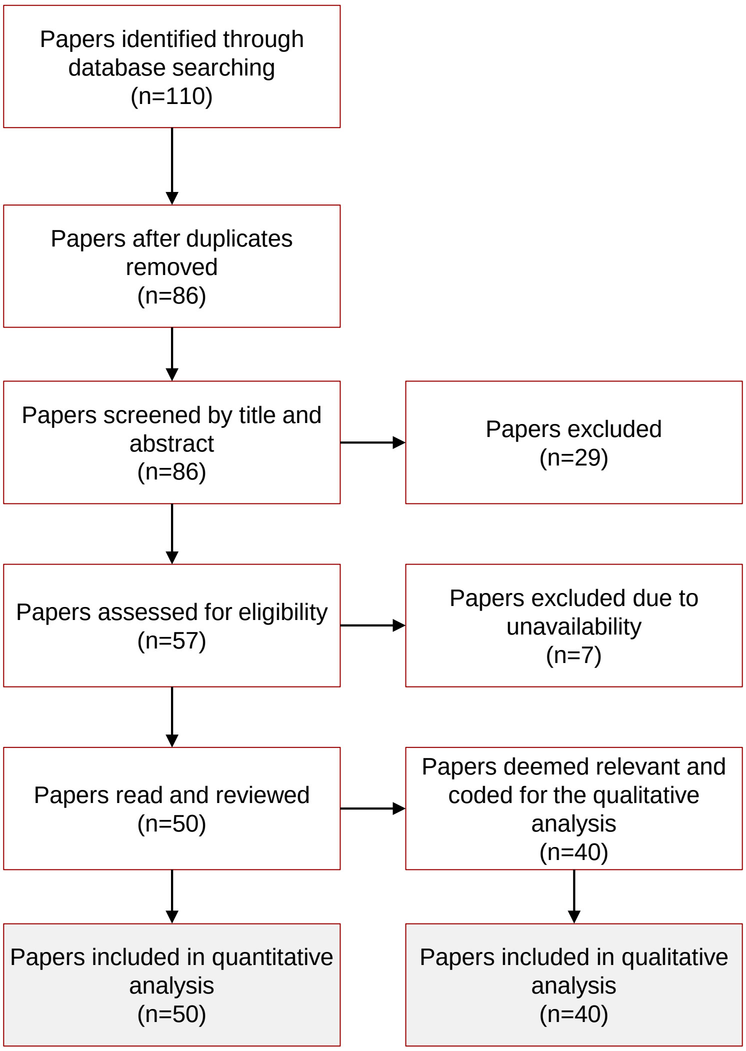

Figure 2 – The PRISMA flowchart specific to the systematic literature review of this paper

The database searches in the identification stage resulted in 110 papers eligible for further screening. Because some publications included several of the Industry 4.0-related keywords, the 110 papers included several duplicates. After removing these duplicates, this number became 86. In the screening stage, we screened 86 papers by title and abstract with the intention of removing papers not relevant to the topic of HF/E in Industry 4.0. Examples of papers excluded were papers on autonomous street vehicles and smart cities. After the screening stage, 57 papers remained. Seven of the 57 papers were unavailable resulting in 50 papers included in the literature review. After reading and reviewing these 50 papers, we only deemed 40 papers as relevant, consequently only coding these 40 publications. We excluded the remaining 10 publications because they either did not include any relevant HF/E-related content or were conference papers published prior to a journal article by the same authors and with the same content. Therefore, the qualitative data analysis only included these 40 papers. However, to present a holistic picture of the current situation of the publication landscape in academic research on the topic, the quantitative analysis included all 50 papers.

2.3 Data Analysis

We used the computer software Microsoft Excel to organize the quantitative data we collected for each publication, as well as for all the quantitative analysis we performed to investigate to what extent publications on Industry 4.0 are integrating HF/E in their research. To investigate how these publications are integrating HF/E in their research, we organized the papers and the qualitative analysis in the computer software Atlas.ti 8 and conducted the review following a systematic coding process of a template analysis (Brooks, McCluskey, Turley, & King, 2015). We used the three broad types of HF/E categories, physical, cognitive, and organizational, as defined by IEA (2018) as a coding framework to characterize the findings from the literature review. Refer to Table 1 for an overview of the coding framework.

The coding of the literature and the analysis of the qualitative data were a three-phase process following an inductive analysis. The purpose of applying an inductive analysis approach is to allow themes inherent in the raw data to emerge as dominant, frequent, or significant without any constraint from structured methodologies (Thomas, 2006). In the first phase, we read all 50 papers included in the review, highlighting and coding statements, references, and results in accordance with the coding framework in Table 1. In the second phase, we revisited the codes and citations to validate and ensure coherency. During the third phase, we themed the codes across the publications and described and summarized the main points as shown in Section 3.2.

3 Results

The data analysis focused on characterizing the current research on HF/E in Industry 4.0 and building a holistic understanding through both the quantitative and qualitative data, thus, clarifying to what extent, what type of, and how the included academic publications integrated HF/E in their research. The results from the quantitative analysis provided important information on keyword and topic trends, the growth of the academic field over the years, and identified coverage of the three HF/E domains. Compared with the quantitative analysis, the qualitative analysis offered a more comprehensive perspective into the specific topics within HF/E that Industry 4.0 researchers have explored until now. By diving into the context of the papers, it was possible to highlight characteristics and focus of the current research within the topic of HF/E in Industry 4.0.

3.1 Quantitative Data Analysis

In this section, we present the findings from the quantitative data analysis and highlight characteristics of the current research on HF/E in Industry 4.0.

3.1.1 Characteristics of Industry 4.0 Keywords Associated with HF/E

Because of the variety of terms and definitions in this new field of research, searching for academic literature can be unproductive. To get an overview of the reoccurrence of the Industry 4.0 keywords used in the online database searches, we created a Pareto chart that shows the number of papers we found with each Industry 4.0 keyword and the cumulative percentage. Refer to Figure 3 to view this Pareto chart.

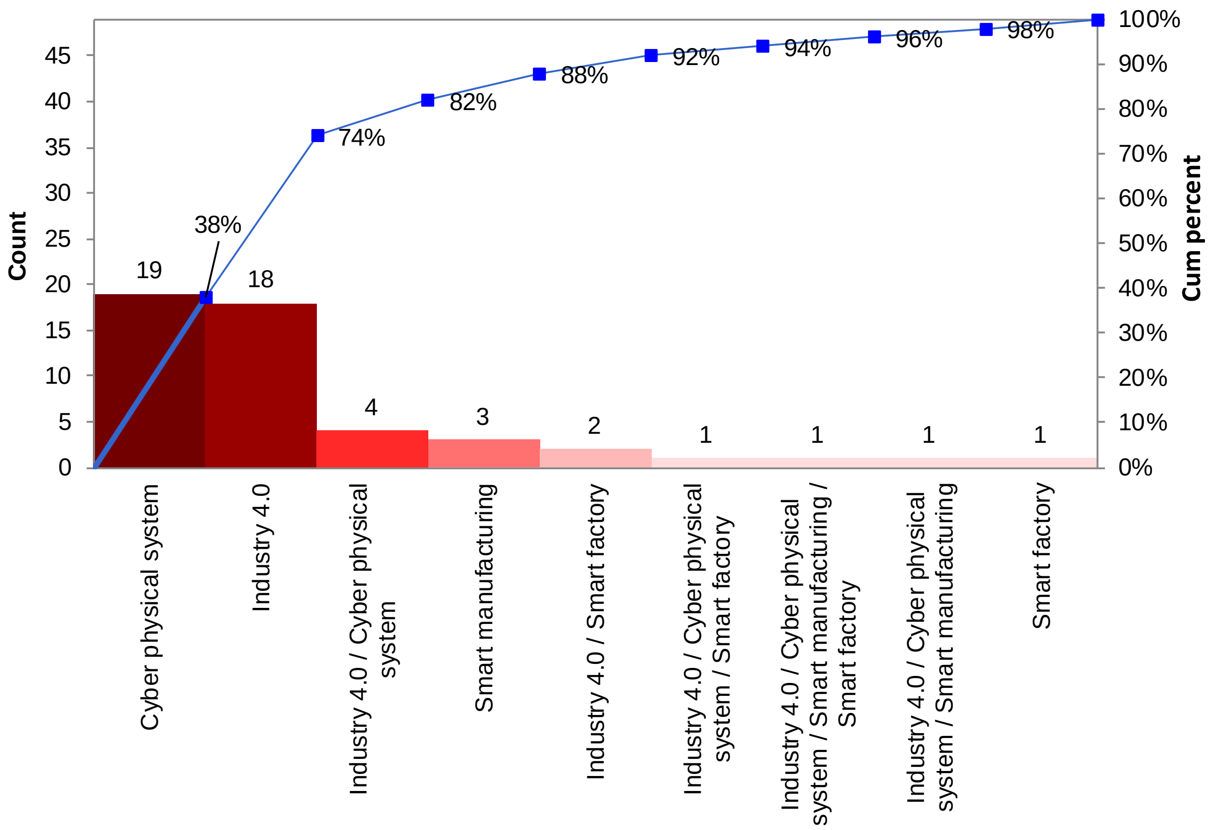

Figure 3 – Pareto chart showing the distribution of Industry 4.0-related keywords used to find the papers in the database searches

Each bar in the Pareto chart represents one or more combinations of Industry 4.0 keywords, meaning that some papers appeared with two or more keywords. *Industry 4.0* and *Cyber Physical System* are the most reoccurring keywords, appearing alone in 19 and 18 papers, respectively. Looking across all of the keywords, these two appear in 47 of the 50 papers, which corresponds to 94%.

3.1.2 Number of Publications by Year

From the years 2013 to 2017, the number of academic publications dealing with HF/E in Industry 4.0 increased exponentially. At the time of this research, June 2018, the number of publications for the year was 11. To put these numbers in perspective, we did two additional searches in the online database Scopus, one with only the Industry 4.0 keywords and another only the HF/E keywords shown in Table 2. *Well-being* is a very common keyword used in thousands of publications across many different research fields. To avoid any exaggeration of the search results, the HF/E keyword search did not include the keyword *well-being*.

Publications in both Industry 4.0 and HF/E fields have increased from 2013–2017, although publications related to HF/E have increased at a slower rate than Industry 4.0. Even though the number of publications on HF/E in Industry 4.0 is increasing, they still make up less than 2‰ of the total number of papers published related to Industry 4.0 and HF/E. Refer to Figure 4 to view the number of publications by years for Industry 4.0 keywords, HF/E keywords, and HF/E + Industry 4.0 keywords.

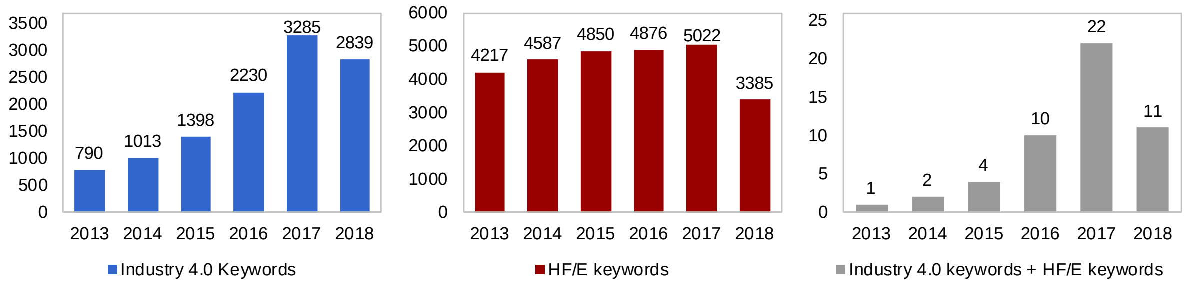

Figure 4 – Column charts showing the number of publications by year for Industry 4.0 keywords, HF/E keywords, and Industry 4.0 + HF/E keywords.

We categorized the publications into the two sources, conference proceedings and journal articles with respect to their original source. Thus, publications from outlets such as Procedia Manufacturing fell into the category of conference proceedings, even though the electronic database, Scopus, categorizes them as journal articles. Out of the 50 included publications dealing with HF/E in Industry 4.0, 37 are conference proceedings and the remaining 13 are peer-reviewed journal articles. Refer to Figure 5 for an overview of publication type by year for the 50 included papers.

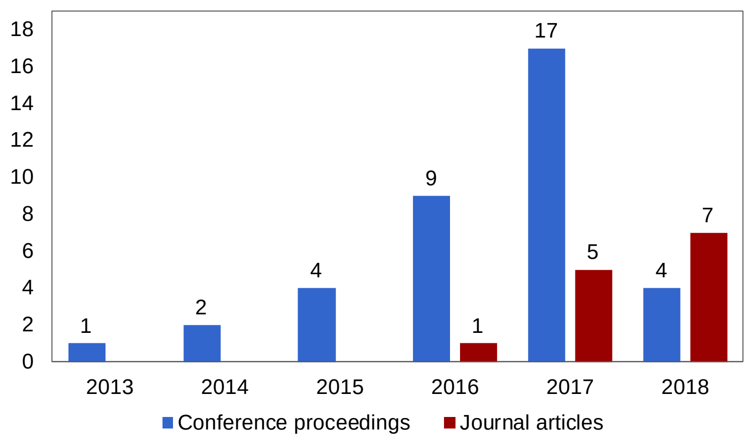

Figure 5 – Publication type by year

3.1.3 Publication Outlets

The 37 conference proceedings are associated with 29 different conferences, 22 of which have only one publication, six have two publications, while only one outlet has published three proceedings. In regard to the journal articles, of the 11 journal outlets, ten journals have each published one article, while one journal has published three. Figure 6 and 7 give an overview of the conference proceedings and journal article outlets, respectively.

Figure 6 - Conference proceeding outlets

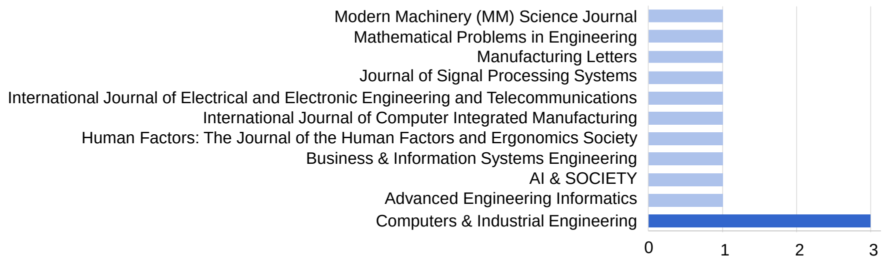

Figure 7 - Journal article outlets

3.1.4 Theoretical vs. Empirical Evidence

Out of the 50 publications included in this research, 26 contribute with theories, conceptual frameworks, and models. The remaining 24 publications contribute with empirical evidence through either case studies and industry data or simulations and laboratory experiments. We attribute the limited number of publications containing empirical data to the novelty of Industry 4.0. Figure 8 shows the distribution of data types in the 50 included publications.

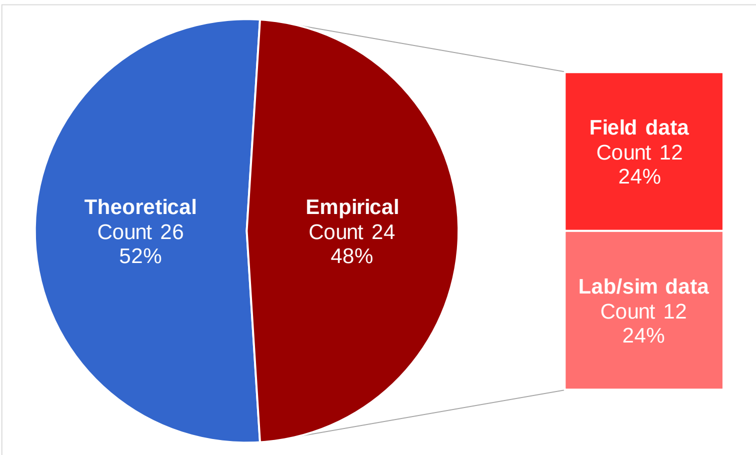

Figure 8 – Distribution of data types in the 50 included publications

3.1.5 Publication Outlets Dealing with HF/E

To get an overview of where academics publish research dealing with HF/E in Industry 4.0, we identified and categorized the publications published in HF/E-relevant outlets. We identified HF/E-related outlets by looking for keywords and terms related to HF/E in the outlets' names. In cases where it was unclear if an outlet was HF/E-related, we gained further information through the outlet's associated website. Refer to Figure 9 for an overview of the number of publications published in HF/E-related outlets.

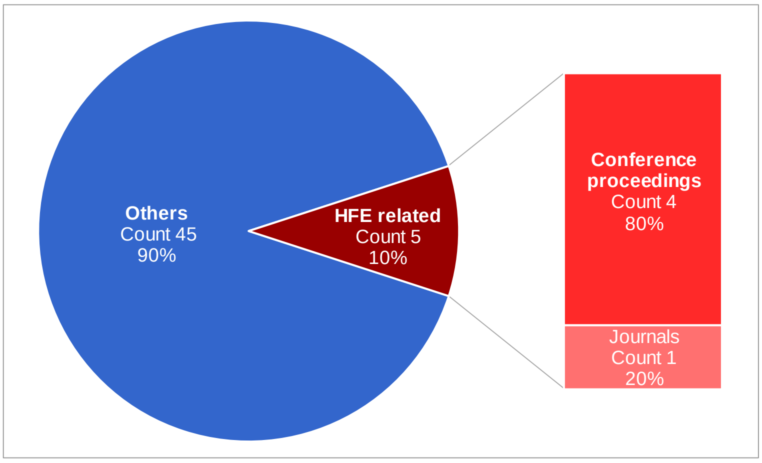

Figure 9 – Overview of the number of publications published in HF/E-related outlets

3.1.6 Categorizing the Current Research into the Three HF/E Domains

By the end of the third and final phase of the coding process, we were able to categorize the included publications into the HF/E coding framework. This categorization highlight which of the HF/E type categories researchers have focused on to date. Refer to Figure 10 for an overview of this categorization.

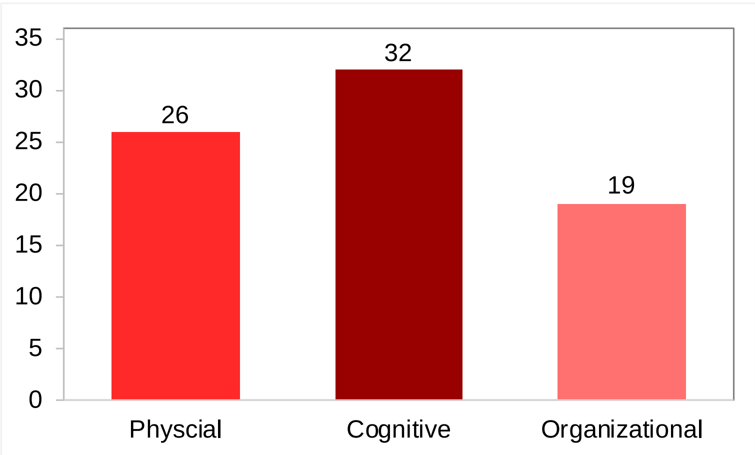

Figure 10 – Summary of number of publications coded in each category of the coding framework

The results in Figure 10 show the distribution between physical, cognitive, and organizational HF/E. Refer to Table 3 for an overview of the specific articles coded in each category of the coding framework.

Table 3 – The distribution of the included papers into the coding framework

Physical	**Cognitive**	**Organizational**
Becker & Stern 2016**;** Hummel, Hyra, Ranz, & Schuhmacher 2015; Müller, Gust, Feller, & Schiffmann 2015; Römer & Bruder 2015; Fantini, Pinzone, & Taisch 2018; Fantini et al. 2016; Kerpen et al. 2016; Richert, Shehadeh, Müller, Schröder, & Jeschke 2016; Romero et al. 2016; Vysocky & Novak 2016; Dombrowski, Stefanak, & Perret 2017; Gašová, Gašo, & Štefánik 2017; Horváth & Erdős 2017; Huber & Weiss 2017; Paritala, Manchikatla, & Yarlagadda 2017; Peruzzini, Grandi, & Pellicciari; 2017; Peruzzini & Pellicciari 2017; Scheuermann, Strobel, Bruegge, & Verclas 2016; Stern & Becker 2017; Dannapfel, Bruggräf, Bertram, Förstmann, & Riegauf 2018; Rylnikova, Radchenko, & Klebanov 2017; De Felice, Petrillo, & Zomparelli	Becker & Stern 2016; Dworschak & Zaiser 2014; Theis, Wille, & Alexander 2014; Hummel et al. 2015; Kim, Kang, Kim, & Chun 2013; Fantini et al. 2016; Richert, Shehadeh, Müller, et al. 2016; Romero et al. 2016; Cohen, Faccio, Galizia, Mora, & Pilati 2017; Czerniak, Brandl, & Mertens 2017; Gašová et al. 2017; Lazarova-Molnar, Mohamed, & Shaker 2017; Ma et al. 2018; Mazali 2018; Pacaux-Lemoine et al. 2017; Peruzzini & Pellicciari 2017; Repta, Moisescu, Sacala, Dumitrache, & Stanescu 2015; Stary & Weichhart 2017; Stern & Becker 2017; Fantini et al. 2018; Richter et al. 2018; Schlagowski, Merkel, & Meitinger 2017; Gopalakrishna, Ozcelebi, Lukkien, & Liotta 2017; Vernim, Walzel, Knoll, & Reinhart 2017; Rylnikova et al. 2017; Pinzone et	Becker & Stern 2016; Dworschak & Zaiser 2014, Hummel et al. 2015; Müller et al. 2015; Fantini et al. 2016; Kerpen et al. 2016; Romero et al. 2016; Vysocky & Novak 2016; Cohen et al. 2017; Mazali 2018; Pacaux-Lemoine et al. 2017; Stern & Becker 2017; Dannapfel et al. 2018; Fantini et al. 2018; Richter et al. 2018; Pinzone et al. 2018; Gurjanov, Zakoldaev, Shukalov, & Zharinov 2018; Vernim et al. 2017; Kadir et al. 2018

2018; Richter, Heinrich, Stocker, & Schwabe 2018; Kadir, Broberg, & Conceicao 2018; Borisov et al. 2016; Richert, Shehadeh, Müller, Schröder, & Jeschke 2016	al. 2018; Spichkova, Zamansky, & Farchi 2015; Richert, Shehadeh, Müller, et al. 2016; Repta, Moisescu, Sacala, Stanescu, & Neagu 2015; Singh & Mahmoud 2017; Kadir et al. 2018; Kerpen et al. 2016	

3.1.7 Summary of the Quantitative Data Analysis

There are several terms related to the concept of Industry 4.0, and the results from the quantitative data analysis showed that the keywords *Industry 4.0* and *Cyber Physical System* are the most reoccurring in academic publications that deal with HF/E in Industry 4.0. The results also highlight the lack of attention HF/E has received in Industry 4.0 research. The number of publications focusing on HF/E in Industry 4.0 has increased since the introduction of the term *Industry 4.0* in 2013, yet this number is incremental in comparison with the total number of publications published since 2013 related to Industry 4.0 and HF/E separately. In addition, the distribution of the HF/E categories is similar, with cognitive HF/E being the most populated.

3.2 Results from Qualitative Data Analysis

In this section, we present some of the most important findings from the themes emerging within each of the HF/E categories with the intent of answering how the included publications integrate HF/E into their research. The qualitative data analysis focused on highlighting the prevailing results and discussions of importance to HF/E in Industry 4.0 coded in the three HF/E categories. The statements we present in this section are not estimations, predictions, or subjective views of the authors of this paper, but are the findings from the qualitative data analysis of the literature review. Refer to Table 4 for an overview of the qualitative data analysis results.

Table 4 – Overview of the qualitative data analysis results

Physical	**Cognitive**	**Organizational**
• Manual repetitive tasks are getting automated. • Close human–machine collaboration evokes safety concerns. • Wearable and handheld devices are improving ergonomic feedback. • New digital technologies are improving internal logistics and transportation.	• Virtual models improve perception and create timely interactions. • CPS are introducing new forms of human–machine interactions. • Problem-solving and IT skills will become a necessity. • Augmented Reality devices will contribute to the reduction of mental strain. • Data sharing across departments is improving cognitive ergonomics. • Technology forecasting can identify necessary skills early on.	• Hybrid production systems are bridging the gap between humans and machines. • New human–machine interactions will affect work organization and design. • Human-centered design will benefit workers. • Work organization is expanding across departments. • The combination of new technology and work organization will determine future skills' development.

3.2.1 Physical HF/E

3.2.1.1 Manual repetitive tasks are getting automated

A frequently mentioned aspect in regard to HF/E in Industry 4.0 was the automation of manual tasks, which is one of the most notable characteristics attributed to Industry 4.0. Numerous publications highlighted and mentioned a future scenario where companies will have automated, easy, repetitive manual tasks (Kerpen et al., 2016; Richter et al., 2018; Stern & Becker, 2017). However, it is also stated that most of the automation technologies in industry have limited flexibility (Dannapfel et al., 2018; Hummel et al., 2015; Kadir et al., 2018). Complex tasks that require flexibility and ad hoc problem-solving skills will still belong to human workers, making them a necessity in the factories of the future (Fantini et al., 2016; Richert et al., 2016; Romero et al., 2016).

Advancements in traditional industrial robots and collaborative robots (cobots) are considered as one of the more prevalent technologies in the automation of repetitive, monotonous, and physically straining tasks (Kadir et al., 2018; Romero, Wuest, Stahre, & Gorecky, 2017). It is mentioned that hybrid teams of humans and robots will support demographic and diverse team structures, and the physical limitations of human workers are compensated through human–robot interactions, where robots help workers lift heavy items or take over other physical tasks. A step further in the direction of human–robot collaboration will be autonomous robots identifying and adapting to workers' individual strengths and taking on the role of an equal supportive workmate (Richert, Shehadeh, Müller, et al., 2016a).

3.2.1.2 Close human–machine collaboration evokes safety concerns

Several publications included in the literature review highlighted concerns regarding workers' safety when working in CPS. This was especially relevant in the case of cobots. Unlike traditional industrial robots, cobots are estimated to be highly reliable in terms of safety and can work side-by-side with humans without the need for any fencing or enclosure (BSI Group, 2016). However, Vysocky & Novak 2016 highlight that cobots, as well as robots, are only as safe as the tools they operate. Everything that is fastened or attached to the cobot/robot can cause its safety to decrease. To overcome these safety concerns, it is suggested that companies use digital/virtual twins to simulate various scenarios to evaluate the human–robot collaboration and collision detection (Horváth & Erdős, 2017). Alternatively, it is proposed that companies could incorporate hands-free gesture control in human–robot interactions to accommodate operational safety, physical ergonomics, and efficiency (Horváth & Erdős, 2017; Scheuermann et al., 2016).

3.2.1.3 Wearable and handheld devices are improving ergonomic feedback

It is mentioned that wearable and handheld digital devices, such as smartphones and smart watches that are able to measure workers' exercise activity levels, heart rate, and other health-related metrics, as well as GPS location, will contribute to the improvement of physical ergonomics in the factories of the future (Romero et al., 2016). On the one hand, Borisov et al. (2016) argued that these devices raise the awareness of workers in regard to physical ergonomics and promote more sensible behavior while working. On the other, Hummel et al. (2015) and Peruzzini et al. (2017) mentioned that the data these devices produce while tracking the workers along with CPS data, creates a unique opportunity to drive process configuration, planning, and smart adaptation of manufacturing systems in accordance with workers' behaviors and stress conditions. However, using such personal and somewhat sensitive data may be rather complicated. Huber and Weiss (2017) highlighted that companies might face privacy issues if they start collecting data without consent from the workers.

3.2.1.4 New digital technologies are improving internal logistics and transportation

It was highlighted that the transition to CPS is happening across company departments and is not limited to individual workstations on the factory floors. It is estimated that considerations regarding physical ergonomics are a focus as companies increase automation of internal logistics and transportation between various locations on the factory floors, as well as across departments. Hummel et al. (2015) mention that the improvement of the science driving technologies such as Automated Guided Vehicles and intelligent continuous conveyors is now allowing these technologies to roam autonomously side-by-side and in the same area as workers.

3.2.2 Cognitive HF/E

3.2.2.1 Virtual models improve perception and create timely interactions

It is mentioned that virtual models, 3D drawings, and virtualization of entire supply chain processes are improving the perception and understanding of planned changes between different company departments and organization layers. This improvement of perception and understanding is estimated to enable timely interaction between different departments that need to collaborate in problem-solving and decision-making (Mazali, 2018).

3.2.2.2 CPS are introducing new forms of human–machine interactions

Lazarova-Molnar et al. (2017) highlight that regardless of the increasing tendencies of automation in industry, CPS' will still include humans, thus, some sort of human–computer/machine interactions will remain. The two most discussed human–computer/machine interactions prevailing in the literature are Human-in-the-Loop (HitL) and Human-in-the-Mesh (HitM).

HitL scenarios are described to involve human activities, such as overseeing and adjusting machines, directly commanding the system, and first in line to detect and report abnormalities (Fantini et al., 2016). This paradigm of HitL combines data and decision models with human knowledge and feedback, which promotes the development of machine intelligence (Ma et al., 2018). It is mentioned that in HitM scenarios, the role of humans is more focused on supporting the systems in activities such as receiving alerts, intervening when necessary, analyzing and changing planning, and observing and extracting knowledge (Fantini et al., 2016). However, Fantini et al. (2016) also mentioned that HitM still lacks a clear definition.

3.2.2.3 Problem-solving and IT skills will become a necessity

It is highlighted that the increasing automation of manual work will support and benefit workers, however, it will also change the skills and competence requirements demanded of workers. Several publications mentioned that the prevailing skills will include the capability to understand abstract information, solve complex problems, and have IT literacy (Becker & Stern, 2016; Dworschak & Zaiser, 2014; Fantini et al., 2016; Kerpen et al., 2016; Lazarova-Molnar et al., 2017). Of the 32 publications coded in the cognitive ergonomics category, 12 of them mentioned the changes in skills and competence requirements. However, most of the data presented were based on estimations and predictions for the future and did not provide any more specific details than the ones mentioned in this section.

3.2.2.4 Augmented Reality devices will contribute to the reduction of mental strain

Augmented Reality (AR) and its use on factory floors was mentioned to contribute to the reduction of mental strain of workers. AR provides a visual layer of information on top of the real-world factory environment through devices such as head-gear, smart glasses, smartphones and tablets, and spatial AR projectors (Romero et al., 2016). It was further noted that AR would have an important role in improving the cognitive ergonomics of workers. It was also estimated that AR technologies can support highly complex and stressful work by removing unnecessary information and provide the workers only with the information they need (Theis et al., 2014). Pinzone et al. (2018) highlighted that the information such technologies might provide could be item codes, names of components, or instructions to help workers remember maintenance and repair procedures. However, Czerniak et al. (2017)

emphasized that it is important to not overload workers with information, thus, causing information overload and increasing mental strain instead of reducing it.

3.2.2.5 Changing demographics creates new demands for factories of the future

Peruzzini & Pellicciari (2017) mentioned that demographic changes and national regulations regarding late retirement, as well as improved health, are allowing workers to stay on the job market for a longer time. Thus, aging workers (45–64 years old) in the industrial sector are increasing in the EU, as well as worldwide. In addition, it was highlighted that political conditions have resulted in increased employment of workers with an immigrant background in European countries (Kerpen et al., 2016).

These new conditions were estimated to be creating new challenges in regard to training, competence development, and human–machine interactions. Therefore, it would be important to adopt a social perspective to improve the assistance of aging, disabled, and apprentice workers with the use of new digital technologies (Romero et al., 2016). Kerpen et al. (2016) used an example, which included an AR device that can automatically adjust its settings depending on the workers using it. In the case of an older worker, the font could enlarge or, in the case of workers with language barriers, the device could show pictograms to create better understanding.

3.2.2.6 Data sharing across departments is improving cognitive ergonomics

It was highlighted that the availability of data across various departments and layers of a company is promoting new ways of planning work with consideration for cognitive ergonomics. Digital planning systems are able to produce Key Performance Indicators that can describe the actual status of a production system and provide real-time individual ergonomics data showing the stress status of the workers. Hummel et al. (2015) mentioned that this kind of data provides quantitative measurements, which other departments in a company, such as planning, can use to plan work and activities, thus, being able to adjust their interactions with the workers on the shop floor accordingly.

3.2.2.7 Technology forecasting can identify necessary skills early on

It is mentioned that the changing requirements to workers' capabilities and skills mean that companies will need to invest in training and skill development (Pacaux-Lemoine et al., 2017). Before any training can take place, the companies have to identify the prevailing skills their workers will need in the near future. Dworschak & Zaiser (2014) suggested that already before companies invest in any new technologies, strategic level decision-makers could take preliminary steps in identifying the needed skills and training by performing technology forecasting. Technology forecasting is a method for anticipating and understanding promising future technologies and evaluating their potential and application at an early point in time (Firat, Woon, & Madnick, 2008). Dworschak & Zaiser (2014) suggest that technology foresight can prepare companies for what capabilities and skills they may need 3–5 years into the future.

3.2.3 Organizational HF/E

3.2.3.1 Hybrid production systems are bridging the gap between humans and machines

CPS and the combination of human workers and automated production parts are said to be creating hybrid productions systems that rely on close human–machine collaborations and new tasks connected to computational devices (Becker & Stern, 2016). Mazali (2018) and Stern & Becker (2017) mentioned that this type of system may reduce organizational losses with mobile assistance systems, intelligent automation, expert knowledge, and workers' creativity. Furthermore, it is suggested that automated and collaborative communication between machines, humans, and systems might replace many aspects of traditional ways of managing, planning, and controlling activities. This will result in new activities that will affect social sustainability performance from a technological and management standpoint (Pinzone et al., 2018).

However, it is mentioned that most of these statements are merely estimates and predictions and do not provide enough depth to the underlying challenges related to this new way of working. Fantini et al. (2018) highlighted that current studies have yet to address challenges, such as how to understand and control interactions between CPS technologies and human workers, how to capture value-added work (decision-making and problem-solving, creative work, social behavior), and how to account for workers' skills and characteristics.

3.2.3.2 New human–machine interactions will affect work organization and design

It was mentioned that as the demand for new competencies changes, the current approaches toward work design and resource management would need to change too. Stern & Becker (2017) suggested that classic job design would need an upgrade to include other elements, such as usability, user interface, and human–machine interactions, in addition to new objectives. For example, in human–robot collaboration, it was mentioned that it is important to analyze the tasks and make a clear division between what activities robots and humans will perform (Dannapfel et al., 2018; Kadir et al., 2018). Furthermore, it was suggested that in the integration of HitM, human competencies and organizational factors would both have a relevant role. Fantini et al. (2016) suggest that due to the complexity, variability, and unpredictability of HitM integration, companies must consider organizational factors to influence positive human behavior and performance.

However, Richter et al. (2018) suggest that there is a need for research on the process of studying and designing tools and digital environments, how companies can introduce digital support for workers, and in which context digital work design is happening. Thus, it is still unknown how the combination of technology and work organization will evolve in the factory of the future.

3.2.3.3 Human-centered design will benefit workers

It is estimated that CPS will directly affect workers and create new interactions between humans and machines and the digital and physical world. Therefore, transformation into Industry 4.0 will require new design and engineering philosophies that are human-centric and focus on enhancing and augmenting the human's physical, sensorial, and cognitive capabilities, rather than unmanned autonomous factories (Romero et al., 2016). There were two proposed scenarios for designing CPS: the techno-centric perspective states that human work will be determined by technology, while in the anthropo-centric scenario, workers will be in control and make decisions supported by the CPS (Pacaux-Lemoine et al., 2017).

The techno-centered design is estimated to require workers to behave flawlessly, have a suitable response time, and react perfectly when facing unexpected situations, which is an overstatement of the workers' abilities. Whereas, using a human-centered design when designing intelligent manufacturing systems would improve the global performance of complex and conflicting production objectives and reduce workers' workload (Pacaux-Lemoine et al., 2017).

3.2.3.4 Work organization is expanding across departments

Automated and collaborative communication between machines, humans, systems, and departments is estimated to replace many aspects of traditional ways of organizing, managing, planning, and controlling activities. Pinzone et al. (2018) suggest that this will result in new activities that will affect social sustainability performance from a technological and management standpoint. Furthermore, it is suggested that shared responsibility, proactive positions, and participatory roles across the company are a part of the Industry 4.0 paradigm, and they are restructuring the work relationship on a collective and individual level. Mazali (2018) mentioned that responsibility and decision-making will not be exclusive to the managers in charge, but also include the workers.

3.2.3.5 The combination of new tech. and work organization will determine future skills development

While it is mentioned that the integration of CPS and the increase of new digital technology implementation will demand new skills and competencies, it is also highlighted that it will not be the only determining factor. Dworschak & Zaiser (2014) argue that the combination of new digital technology and work organization chosen in a company will have a determining role in further skills and competence development.

3.2.4 Summary of the Qualitative Analysis

The results from the qualitative analysis provide a fair idea of how the included academic publications dealt with HF/E. In this section, we give a short summary of the results obtained through the qualitative data analysis and highlight the prevailing topics mentioned to have an effect on the physical, cognitive, and organizational ergonomics related to human work in Industry 4.0.

In regard to the domain of physical ergonomics, we highlighted four topics. These four topics covered the increasing automation of manual tasks, safety concerns evoked by close human–machine interactions, how wearable and handheld devices are contributing to the improvement of ergonomics, and how new digital technologies will improve internal logistics in Industry 4.0 companies.

In the domain of cognitive ergonomics, we highlighted the following six topics: Upgrading the workers’ problem-solving and IT skills will become a requirement in Industry 4.0. CPS will introduce new forms of human–machine interactions. AR devices could help reduce workers’ mental strain. Data sharing across company departments and virtual models could have positive effects on workers’ perception and decision-making. Finally, yet importantly, how using technology forecasting could help with the identification of future skills.

In the domain of organizational ergonomics, we highlighted the following five topics: Hybrid production systems are bridging the gap between humans and machines. New human–machine interactions will have an effect on work organization and design. Using a human-centered design in CPS would benefit the workers. Work organization is expanding across departments. The combination of new technology and work organization will determine future skills' development.

Finally, while conducting the qualitative analysis, we noticed that the included publications predominantly favored pinpointing and highlighting opportunities and benefits over challenges and downsides of Industry 4.0 and the implementation of new digital technologies.

4 Discussion

4.1 Contribution

The contribution of this paper is the establishment of to what extent, what type of, and how academic publications on Industry 4.0 integrate HF/E into their research. Thus, highlighting research gaps and areas of focus for future research on HF/E in Industry 4.0. The following are some of the main findings of this paper. The extent of Industry 4.0 research dealing with HF/E is small. Surprisingly, Industry 4.0 research has covered HF/E aspects much better in comparison with research within the HF/E discipline. In addition, the research dealing with HF/E aspects were often theoretical/hypothetical and not developed on empirical research. Most focus on the operational level—overlooking the importance of tactical and strategic levels for the success of HF/E.

4.2 Current Research on HF/E in Industry 4.0

The results from the systematic literature review and the quantitative analysis confirm that Industry 4.0 research dealing with HF/E is limited. While the number of publications on Industry 4.0 research dealing with HF/E has been increasing from 2013 to 2018 (going from one in 2013 to 22 and 11 publications in 2017 and mid-2018, respectively), it is still relatively low. As highlighted in Figure 4 in Section 3.1.2, these numbers are a fraction of the number of publications published on the topics of Industry 4.0 and HF/E separately during the same time span. The initial recommendations for implementing the strategic initiative of Industry 4.0 in Germany (Kagermann et al., 2013) included a focus on research on human work and work organization. From the findings presented in this paper, it is clear that academic research published in English does not accommodate this recommendation very well. Thus, the extent of research in the overlap between the research field of Industry 4.0 and HF/E is limited.

An important element to highlight is the limited empirical evidence that accommodates statements and predictions on how the move toward Industry 4.0 might affect HF/E in industrial companies. As highlighted in Section 3.1.4, around 52% of the publications included in this paper covered the topic of HF/E in Industry 4.0 with theories, estimations, and predictions. In addition, very few of the topics we presented in Section 3.2, which were highlights from the findings of the qualitative data analysis, included empirical evidence. When discussing HF/E in Industry 4.0, the included publications focused on presenting future scenarios, challenges, and opportunities, rather than current findings related to the current state of industry. The following are some examples of such statements.

The estimations of future scenerios where easy tasks are automated (Section 3.2.1.1). Change in skills and competence requirements demanded of workers (Section 3.2.2.3). Automated and collaborative communication between machines, humans, and systems may replace many aspects of traditional ways of managing, planning, and controlling activities (Section 3.2.3.1). Because the publications do not have a foundation of descriptive empirical evidence to support their claims and predictions, they lack the necessary power to present any strong prescriptive actions to overcome the emerging challenges and opportunities.

The qualitative analysis also showed that current research on HF/E in Industry 4.0 is more concerned with lower operational level topics and put a limited focus on the topics related to upper organizational levels. This is in coherence with Pacaux-Lemoine et al. (2017), who also make similar statements. Finally, the majority of research on HF/E in Industry 4.0 is from non-HF/E focused publication outlets, thus, our evaluation is that the majority of the researchers behind the publications are not highly familiar with the HF/E domain, thus, their research approach and perspectives may differ from the typical HF/E researcher. This was evident in many of the included publications in their ways of describing and referring to HF/E. A recurring example was the term "ergonomics," which in many non-HF/E publications outlets was used solely in reference to physical ergonomics and physical strain.

4.3 Future Perspectives for HF/E in Industry 4.0

The findings from the qualitative analysis indicate that researchers, for the most part, are in conformity regarding their predictions and estimations on how Industry 4.0 and new digital technologies might affect humans and work in industry. However, as mentioned in Section 4.2, descriptive empirical evidence is scarce, thus most prescriptive actions and recommendations are untested and lack practical application. Having this lack of empirical data in mind, we propose the following agenda for research on HF/E in Industry 4.0.

4.3.1 Increasing Focus on Empirical Data

To provide practitioners with valid prescriptive actions that enable them to tackle the changing demands of HF/E in Industry 4.0, there is a need for descriptive empirical evidence and tested hypotheses. In addition, empirical evidence is highly important in the creation of a solid foundation that can carry future research within this field in academia. From our perspective as researchers, we find it of great importance to have a sufficient understanding of the HF/E challenges and opportunities that are emerging with the implementation of new digital technologies. This information is paramount in dictating the direction of future research in academia as well as driving HF/E-related solutions and strategies in industry. The results of this paper are a clear indication of how limited this type of empirical evidence in HF/E research is in academia.

Industrial case studies are a great way of collecting empirical data, which could lead to new interesting findings and fresh theories that connect qualitative evidence to mainstream deductive research (Eisenhardt & Graebner, 2007). Flyvbjerg (2006) argues that even single-case studies have their benefits and are a sufficient method for certain important research tasks. Extensive industrial case studies with rich data presentation could be a step in the right direction in validating or rejecting many hypotheses on the changes in human work in Industry 4.0.

Furthermore, we suggest that researchers strive to test conceptual tools, methods, and designs outside of the enclosed walls of controlled laboratories. Rigorous testing in real-life industrial scenarios may highlight the shortcomings of a concept and provide insights and further development. However, this is a two-way street, which is why we suggest and encourage closer collaboration between academia and industry.

4.3.2 Adopting a Holistic Research View on HF/E in Industry 4.0

As we highlighted in Section 4.2, much of the HF/E research in Industry 4.0 focuses on the emerging changes on the operational level and pays little attention to the tactical and strategic organizational levels. Dul & Neumann (2009) highlight the importance of incorporating HF/E in company strategies, which we assess to be ever more important in the transition to Industry 4.0. While the strategic level of a company makes decisions related to the investment of new digital technologies and implementation of CPS, the tactical level focuses on the (re)design of work systems and implementation of new solutions. To ensure sufficient attention to HF/E in Industry 4.0, it is our belief that it is essential to consider HF/E aspects on all three organizational levels.

To accommodate this need, it is important to widen the scope of research on HF/E in Industry 4.0 to include all three organizational levels spanning across the three main domains (physical, cognitive, and organizational) of HF/E, as well as the interplay between them. In addition, due to the novelty of Industry 4.0 and the current limited understanding of the appertaining changes in human work, it might be necessary to explore new territories outside of these three HF/E domains. We suggest that a new research scope should serve to provide a holistic view of HF/E in Industry 4.0 and the effects of pertaining changes on the different aspects in the domains of HF/E. Furthermore, it might be beneficial for researchers exploring HF/E in Industry 4.0 to follow an existing holistic approach such as or similar to the Work System Method (Alter, 2006).

5 Limitations of the Paper

Identifying what terms to include in the literature search was one of the initial aspects we had to consider while working on this paper. On the one hand, the term “Industry 4.0” is popular and commonly used to describe the current digitalization agenda in industry, however, there are other terminologies and words academic publications might use to describe the same concept. On the other hand, some publications might solely focus on one technological aspect and refrain from using any terminologies related to the overall concept associated with Industry 4.0. This different use of words and terminologies might leave room for overlooking relevant publications. Even though we have been very careful in selecting the search terms and did the utmost to be as inclusive as possible without making the search too wide, it is difficult to eliminate the probability of having overlooked publications.

6 Conclusions

Using a Human Factors and Ergonomics (HF/E) approach to analyze, understand, and design human work and Cyber Physical Systems in Industry 4.0 could be highly beneficial. However, due to the novelty of the Industry 4.0 concept, further research within this narrow field is in high demand. In this paper, we conducted a systematic review on HF/E research in Industry 4.0 with focus on investigating the manner and to which extent academic publications on Industry 4.0 integrate HF/E aspects into their research. On the basis of these findings, we present future perspectives for research on HF/E in Industry 4.0.

Our findings show that academic publications dealing with this specific topic are scarce. The majority of the publications are conference proceedings and a low percentage of the publications come from HF/E-related publications outlets. The data from these publications are very heavy on estimations and predictions on future scenarios and present limited novel descriptive empirical data. Thus, many of the prescriptive actions and recommendations these publications suggest are unfounded and untested. In addition to these findings, we present a future perspective for HF/E in Industry 4.0, which includes recommendations for future research approaches to HF/E in Industry 4.0. Such recommendations include increased focus on empirical evidence to establish a baseline for the challenges and opportunities emerging with new digital technologies and Industry 4.0 and widening the research scope to include all three organizational levels (strategic, tactical, and operational), rather than the current situation, which is primarily focused on the operational organizational level.

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