ARTICLE IN PRESS

Computers & Industrial Engineering xxx (xxxx) xxxx

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Anthropocentric perspective of production before and within Industry 4.0

Erwin Rauch[a,*], Christian Linder[b], Patrick Dallasega[a]

[a] Faculty of Science and Technology, Free University of Bozen-Bolzano, Piazza Università 5, 39100 Bolzano, Italy
[b] Management Department, ESCP Europe Business School, London Campus, UK

ARTICLE INFO

Keywords:
Anthropocentric production
Industry 4.0
Cyber-physical production systems
Operator 4.0
Systematic literature review
Human-centred production

ABSTRACT

This paper presents a systematic literature review (SLR) of the anthropocentric perspective of production before and after (or, better, within) Industry 4.0. We identify central research clusters regarding traditional Anthropocentric Production Systems (APS) and Anthropocentric Cyber Physical Production Systems. By comparing the two perspectives, we are able to analyse new emerging paradigms in anthropocentric production caused by Industry 4.0. We further make prediction of the future role of the human operator, his needed knowledge and capabilities and how assistance systems support the Operator 4.0. Our paper gives a brief outlook of current and needed future research. It builds grounds for further scholarly discussion on the role of humans in the factory of the future.

1. Introduction

Over the past decades, technology-oriented manufacturing approaches, computer-integrated manufacturing, lean management and cellular manufacturing have shaped the image of industrial production like few other developments. With the introduction of a human-centred design approach and anthropocentric manufacturing principles, the operator as a qualified and valuable resource has moved in the focus of production (Genaidy & Karwowski, 2003; Treville & Antonakis, 2006). Accordingly, the human operator was given a special place within modern manufacturing concepts – like lean manufacturing – in which the anthropocentric idea of production takes centre stage today (Tortorella & Fogliatto, 2013; Womack, Jones, & Roos, 1990). However, with the arrival of Industry 4.0 and the smart factory, a major change is taking place in the industrial world. The fourth industrial revolution marks a new quality leap in industrial production by linking people, machines and products by forming together a new production system, which enables faster and more targeted exchange of information. This change moves towards a future where people will collaborate with robots and will be supported by web technology and intelligent assistance systems in their work activities (Gorecky, Schmitt, Loskyll, & Zuhlke, 2014).

The digitalisation of production and the demolishing of boundaries between the physical and digital world, hence, causes a deep fear that, in the future, humans may be subservient to machines and automation (Rosenbrock, 1990). We argue in this paper that new and complex work domains possess several characteristics that have important implications for the demands they place on their operators. These demands may affect the role of the operator in Industry 4.0 significantly; but in which way is not foreseeable today. Much of the fear of new upcoming systems and the associated new working conditions result from an unclear comprehension of the role of the human actor in future manufacturing processes. This leads to the question of how and in which way Industry 4.0 will change the role of the operator in production.

Against this backdrop, we review literature of production systems. In particular, we apply a Systematic Literature Review (SLR) in order to map and assess the relevant intellectual territory regarding anthropocentrism in production before and within Industry 4.0 with special attention to human-machine interaction. Based on the identified changes of production systems induced by Industry 4.0, a further aim of the research is to identify if and how tasks and roles of operators have been and/or will be subject to change. As such, based on the investigated current state of research in the fields of anthropocentric production and operator's job responsibilities, future perspectives are proposed. In what follows, we synthesise the actual knowledge to address two open questions. First, we answer the question: 'What is the anthropocentric perspective of production before and within Industry 4.0 with a specific focus on the interface between humans and machines?' Second, we compare the two perspectives, analysing the transformation of research fields in anthropocentric production with the introduction of Industry 4.0. Thus, the second research question is formulated as follows: 'are there major shifts in the anthropocentric perspective of the operator, allowing identifying similarities,

* Corresponding author.
E-mail address: erwin.rauch@unibz.it (E. Rauch).

https://doi.org/10.1016/j.cie.2019.01.018

differences and trends?' Based on the answering of the two research questions we provide a cue for future research to determine how and whether the tasks and the role of the operator has evolved and will change in the future.

With our analysis, we are able to mainly, but not exclusively, contribute to three major discussions regarding the operator in Industry 4.0. To the best of our knowledge, there exists no comparable study regarding the emergence of a new anthropocentric perspective on the operator in Industry 4.0. However, we find much confusion, speculation or vagueness regarding the future role of the human operator. With our study, we are able to add clarification to this discussion by outlining the state-of-the-art in academic research. Our work helps to build a stable foundation for future research. We specify the actual scientific knowledge and structure the existing intellectual territory, which allows future researchers to formulate more precise research programmes.

2. Basic concepts

Anthropocentrism in its widest sense "describes the tendency to imbue the real or imagined behavior of nonhuman agents with humanlike characteristics, motivations, intentions, or emotions" (Epley, Waytz, & Cacioppo, 2007, p. 864). In context of workplace relations, anthropocentrism refers to a focus on the person as an individual and not as just another part of the mechanics of production (Trist & Bamforth, 1951). Companies realized, as a result of the extensive research that followed the Hawthorne studies, that increasing productivity in production was not only a matter of economic incentives. As consequence, an anthropocentric perspective on production systems, which attempts to approach the subject of organisational management psychologically, was seen as more beneficial as strictly relying on scientific management theories like Fordism or Taylorism (Piore & Sabel, 1984). This generated the awareness that the social shaping of technology and work, with particular reference to human centred integration in operation and manufacturing processes is an important mean to increase not only firm performance but also work and life quality of workers (Rauner, Rasmussen, & Corbett, 1988). As consequence, academic made the exploration of human-machine interaction to one of their important research task (Cooley, 1987). Another connotation of anthropocentrism in very early concepts of production is nearly exclusively concerned with non-human animals and natural artefacts. The technological change and the omnipresence of technology in modern societies, later, has merged the boundaries of the concept 'anthropocentrism' towards production and technological systems. Taking the anthropocentric perspective in production seriously leads to the development of APS, defined as structures and processes based on the utilisation of skilled human resources and technology adapted to the needs of a flexible and participative organisation (Kovács & Moniz, 2013). Intended to improve skills, participation in the decision-making processes and the quality of working life, APS are new technologies to valorise specific human capacities (Kovács & Moniz, 1994). The APS concept stretches from plant organisation, via departmental cooperation and group work to the work place (Benders, Haan, & Bennett, 1995). The essential components of APS are: flexible automaton, decentralised organisation of work, flat hierarchies, strong delegation of power and responsibilities, reduced division of labour and a continuous up-skilling of workers (Kovács & Moniz, 1994).

For our purpose, especially the new connectivity and interaction technologies, like smart products, smart machines and smart operators, cause a rethinking of the relation between human and machine. With the anthropocentrism of manufacturing or production systems, we understand, in its broadest sense, the socially suitable interaction between human and machine, both in the digital and physical world. This interaction is a critical relation coined by the social-technical transformation. In particular, we focus on the human-machine interaction exclusively. For this reason, we differentiate our work from behavioural or psychological oriented tradition in industrial relations, where the effects of social relations, motivation and employee satisfaction on factory productivity are the central research interest. Focusing on the interaction between human and machine we address a much newer discussion than the behaviour between human and human and the behaviour of people in groups. Such interaction is subject to a permanent interpretation and re-interpretation regarding the available technologies and technical standards. Thus, every period has developed its own concepts of the relation between of human and machine, and, hence, its own vision of (APS). Today, there are multiple concepts, which understand the machine as a 'partner', which supports and improves the knowledge, competencies and capabilities of the human. As a consequence, the future operator is not fully separable from the technological artefacts used, or the lines between technological systems and humans become blurred. In our paper, the Operator 4.0, comprehended as the 'operator of the future', is the subject of interest; in other words, anthropocentric production is built around a smart and skilled operator, who is supported by machines or assistance systems where and when needed. According to (Romero, Bernus, Noran, Stahre, & Fast-Berglund, 2016), Operator 4.0 represents a new design and engineering philosophy for adaptive production systems centred around the treating of automation as a further enhancement of humans' physical, sensorial and cognitive capabilities.

The fourth industrial revolution, the so-called Industry 4.0 is characterised by linking the multiplied distributed artificial intelligence and by making it available to the human operator. In more detail, the multiplied and distributed artificial intelligence can be explained by Cyber-Physical Systems (CPS), which are computers with networks of small sensors and actuators that are installed as embedded systems in materials, equipment and machine parts and connected via the Internet (Kagermann, Wahlster, & Helbig, 2013). As such, CPSs combine the physical with the real world, by collecting and exchanging data over the Internet under the term of "Internet of Things" (Mukhopadhyay & Subhas, 2014; Rauch, Seidenstricker, Dallasega, & Hämmerl, 2016). An implementation of CPS in production and the development and use of system-based information management has led to factories characterised by human-automation symbiosis, where machines cooperate with humans. However, production systems will not be designed to replace the skills and capabilities of humans, but to assist humans in being more efficient and effective (Nelles, Kuz, Mertens, & Schlick, 2016; Romero et al., 2016; Tzafestas, 2006). Romero et al. (2016) present different Operator 4.0 typologies and enabling technologies for human-automation symbiosis work systems. Moreover, in Romero et al. (2016) evolution stages of operator generations are presented. In Operator 1.0, the human performs manual work and is supported by manually operated machine tools (1700–1960). The Operator 2.0 generation is supported by CAx tools, NC operating systems and enterprise information systems (1960–1970). The Operator 3.0 generation performs cooperative work with robots, machines and computer tools, which is also referred to as human-robot collaboration (1970–2000). Ultimately, the Operator 4.0 generation is characterised by operating in a human-automation symbiosis for enhancing workforce capabilities. As such, Romero et al. (2016) present three types of enhancing workforce capabilities: (1) Automation Aiding for Enhanced Physical Capabilities (e.g. powered exoskeletons for increased strength and endurance of the operator, ergonomic adjustments to correct the posture of the operator); (2) Automation Aiding for Enhanced Sensing Capabilities (e.g. transforming temperature to visible colour, vibration to audible spectrum sound) and (3) Automation Aiding for Enhanced Cognitive Capabilities (e.g. diagnosis, decision-making and planning). To sum up, unlike the Computer-Integrated Manufacturing (CIM) approach, which aimed at fully automated factories without humans, Industry 4.0 aims at a successful application of technology with human-centred (semi-)automation (Nelles et al., 2016).

3. Method and research strategy

In order to review an existing body of knowledge, multiple research strategies are available. This includes quantitative methods like co-citation analysis and meta-analysis as well as qualitative methods like narrative reviews. We apply SLR in our study for several reasons. Most important is that SLR is based on a systematic, method-driven and replicable approach (Booth, Papaioannou, & Sutton, 2012). In this regard,

> "[s]ystematic reviews differ from traditional narrative reviews by adopting a replicable, scientific and transparent process, in other words a detailed technology, that aims to minimize bias through exhaustive literature searches of published and unpublished studies and by providing an audit trail of the reviewers decisions, procedures and conclusions" (Tranfield, Denyer, & Smart, 2003, p. 209).

SLR are commonly understood as a powerful instrument to evaluate published work in a relatively actual scientific field because – other than, for instance, co-citation analysis – it takes into account every source, beyond the number of citations, which naturally are relatively low for recently published works. This especially plays a role if researchers are comparing a relatively settled field like traditional production systems to a new and emerging field like Industry 4.0.

There are various recommendations available for conducting SLRs (e.g., Booth et al., 2012; Petticrew & Roberts, 2006). We follow in our study the SLR process suggested by Denyer and Tranfield (2009), which contains the planning, conducting and reporting stage. Of special interest for our purpose are four consecutive steps (see Fig. 1): *Step 1:* Establishing the research objectives; *Step 2:* Defining the conceptual boundaries of the research; *Step 3*: Setting out the data collection by defining inclusion/exclusion criteria; and *Step 4:* Reporting the validation efforts. As result of this procedure, we finally present the set of literature on which we build our further analysis.

3.1. Establishing the research objectives

The research objectives extrapolate from the research questions. The objective of this study is to understand the current knowledge regarding socially sustainable production systems, with special emphasis on the interaction between human and machines. In particular, we want to understand anthropocentrism in traditional and future production in order to learn about the future tasks and roles of human operators in relation to the machines used.

3.2. Conceptual boundaries

The combination of the two concepts 'anthropocentrism' and 'production' define the conceptual boundaries. There have been some challenges for setting clear conceptual boundaries for this research. One of them is that the actual literature on anthropocentric production lacks a precise definition of the concept 'anthropocentric production', or that definitions alter, especially over time. Since we use this term with a special focus on human-machine interaction, we are not able to rely on the use of the phrase 'anthropocentric production' but need to investigate what is meant with this term. This is a common issue in SLR, particularly if the topic is new and has not developed its boundaries. Hence, we ensure that our proceeding is consistent with recent studies and methodological recommendations. We, further, formulated our conceptual boundaries in reference to the suggestions of Ortenblad (2010) and only limited the field, i.e., production in a sense, that it captured the interaction between humans and machines down to traditional forms of production and the production systems associated with the Industry 4.0 framework. However, we kept the boundaries for 'anthropocentrism' relatively open, due to the existing of multiple and sometimes wage conceptualisations of this term (Purser, Park, & Montuori, 1995). This procedure enables us to have, on the one hand, a clear and precise focus, i.e., production, in which we, on the other hand, find a rich heterogeneity or plurality of anthropocentric concepts. In particular, the overarching concept of anthropocentrism allows us to understand what is done and/or written under these headings or concepts and what authors mean in general terms when they refer to anthropocentrism before and within Industry 4.0.

3.3. Setting the inclusion and exclusion criteria

Besides the conceptual boundaries, we set several search boundaries, in terms of database, search terms and publication period. In particular, we used one electronic database for the keyword search, which we identified as the most relevant. Accordingly, we conducted a keyword search using the *Scopus* database. Aware that there are more databases available, which ultimately may contain further relevant work, we also checked other sources such as ISI Web of Knowledge, ASSIA (Applied Social Sciences Index and Abstracts), Science Direct, EBSCO, ACM (Association for Computing Machinery), PsycINFO, SocINDEX, Library, Information Science and Technology Abstracts, CINAHL, IngentaConnect, Infotrac, IEEE (Institute of Electrical and Electronics Engineers), and Business Source Premier, or Emerald and ProQuest. Because our results did not change after adding these sources, we decided to stay with the Scopus database as it represents the most relevant sources for our particular purpose.

We applied a stepwise search limitation using the search terms 'human-centred', 'anthropocentrism', 'production', 'manufacturing', 'operations', and 'assembly' where appropriate in both British and American English. We further selected sub areas to specify our search. The sub areas included all engineering fields as well as neighbouring fields. We did not limit our search further to published work within a particular time frame since we wanted to include all relevant work, regardless the date of publication. In addition, a limitation to English papers only was set because we intended to focus on internally recognised work exclusively. The question as to which types of publications should be included is somewhat complicated because boundaries may eventually exclude highly relevant work. However, setting boundaries allows researchers to also set quality standards for inclusion of works in the SLR. We decided to secure the highest quality standard by including only sources, which have passed a scholarly review process. Thus, we only included peer-reviewed conference proceedings, journal contributions and book chapters. Table 1 provides an overview

3.4. Validation of search results

In order to justify inclusion into our SLR, we developed a first coding schema regarding the content and the concepts used in the identified studies. Our coding schema was applied to all identified studies. It directly corresponds with our conceptual boundaries as mentioned before. Because reliability and validity issues are central to every SLR we used to ensure high quality standards by testing inter-rater reliability, a recognised process in qualitative research, whereby data are independently coded and the coding is then compared for agreements (Armstrong, Gosling, Weinman, & Marteau, 1997). Another issue is that some authors criticise that researchers tend to rely on the quality rating of a particular journal, rather than applying quality assessment criteria to individual articles (Mulrow, 1994; Tranfield et al., 2003). In respect to this issue, we use a scoring model inspired by Kitchenham and Charters (2007) notion of quality check, whereas independent researchers rate different quality criteria according to a scoring schema with the purpose of identifying less reliable works (e.g., Kitchenham et al., 2010). This is done in addition to the selection of the publication type on the level of individual articles. In reference to Connolly, Boyle, MacArthur, Hainey, and Boyle (2012), we applied a relatively straightforward second coding scheme, which evaluated the appropriateness of a study using scores 1–3 (where 3 denotes high, 2 denotes medium and 1 denotes low on that criterion) and five dimensions. These dimensions address the appropriateness of the research

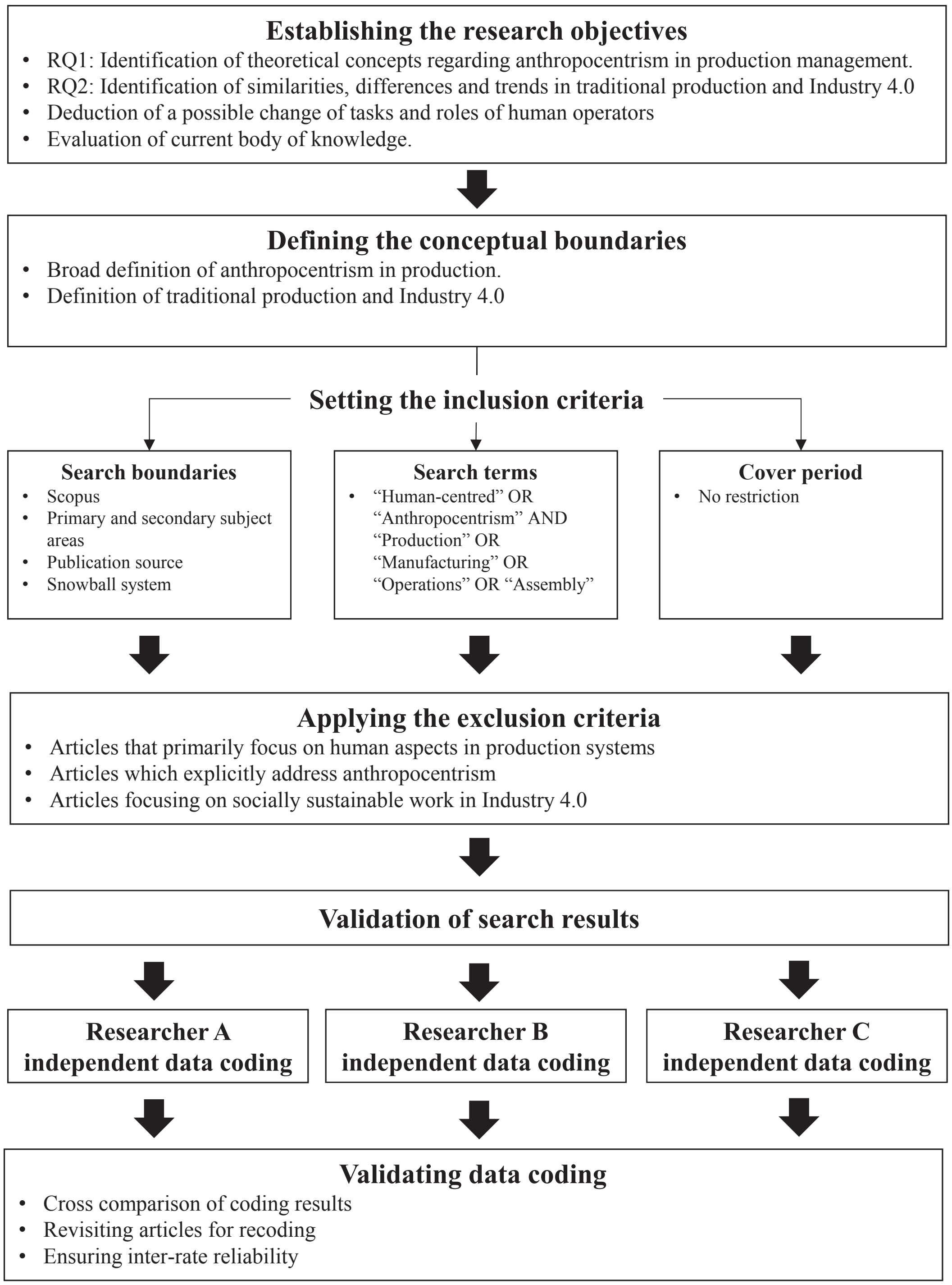

Fig. 1. Applied SLR research process.

design for addressing our research questions, the appropriateness of methods and analysis used, the generalisability of results, the relevance of the focus of the studies, and a general dimension assessing the extent to which findings can be trusted. We calculated the inter-rater reliability for each paper by evaluating the difference in scoring. Where the three independent raters came to the same conclusion, i.e., zero differences or the highest inter-rater reliability, papers were directly included into the analysis. Papers where differences in the coding occurred were excluded if successive iteration did not result in 100% agreement between the three researchers. Using this approach allowed us to ensure that only studies were taken into account, which are consistent in the sense that independent scholars reach the same conclusion reading the study in question. If disagreement cannot be resolved, so the underlying assumption of this method, then at least clarity in the theory, the method, the modelling, the argumentation, or the data generation and analysis is missing, what prevents the study to make a clear and consistent statement. Following pervious researchers, we excluded these papers, since we cannot build a reliable SLR on doubtful papers.

3.5. Descriptive sample overview

We analysed 58 studies of which 31 refer to anthropocentrism before Industry 4.0 and 27 to anthropocentrism after, or within Industry

Table 1
Search terms and search limitation.

Limitation	Criteria	Count
Source	Scopus	
Search terms and connections	“Human-centred” OR “Anthropocentrism” OR “Human-centred” OR “Anthropocentric”) AND (“production” OR “manufacturing” OR “operations” OR “assembly”	452
Sub area	“Engineering” LIMIT-TO “Human Engineering” OR “Automation”) OR “Human Computer Interaction” OR “Computer Simulation” OR “Manufacture” OR “Man Machine Systems” OR “Artificial Intelligence” OR “Decision Making” OR “Ergonomics” OR “Virtual Reality” OR “Computer Integrated Manufacturing” OR “Robotics” OR “Decision Support Systems” OR “Assembly” OR “Production Engineering” OR “Technology” OR “Factory Automation” OR “Flexible Manufacturing Systems” OR “Human-machine Interface” OR “Process Control” OR “Computer Aided Manufacturing” OR “Industrial Engineering” OR “Intelligent Robots” OR “Human Operator” OR” Intelligent Control” OR “Human” OR “Human Machine Interaction” OR “Human Robot Interaction” OR “Industry” OR “Industry 4.0” OR “Manufacturing Systems” OR “Agile Manufacturing Systems” OR “Augmented Reality” OR “Human-centred Automation” OR “Human-centred Computing” OR “Manufacturing System” OR “Process Engineering” OR “Production” OR “Production System”	116
Time	No restriction	
Source type	Conference proceedings, journal contribution, book chapters	79
Screening	Coding and test for inter-rater reliability	62
Language	English	58

Notes: Count refers to the studies left after applying the search limitation.

Table 2
Distribution of published work according to publication type.

	All		Before Industry 4.0		Within Industry 4.0	
	Number	Percent	Number	Percent	Number	Percent
Conference proceedings Annual IEEE International Systems Conference; ASME Design Engineering Technical Conference; IECON Proceedings; IEE Colloquium (4); IEEE International Conference on Emerging Technologies and Factory Automation (3); IEEE International Conference on Industrial Technology; IEEE International Conference on Systems, Man and Cybernetics; IEEE International Symposium on Assembly and Manufacturing; IEEE Conference on Applied Electrical Engineering and Computing Technologies; IEEE/ASME International Conference on Advanced Intelligent Mechatronics; IFAC Proceedings (7); Innovative Production Management towards Sustainable Growth; International Conference on Collaboration Technologies and Systems; International Conference on Computers & Industrial Engineering (1); International Conference on Control, Automation and Systems; International Conference on Management Science and Industrial Engineering; International Conference on Sustainable Intelligent Manufacturing; International MATADOR Conference; Procedia CIRP (2); Proceedings of Manufacturing International, Symposium on Flexible Automation	**33**	**0.57**	**12**	**0.39**	**21**	**0.78**
Journal contribution Automatica; BT Technology Journal; CIRP Annals – Manufacturing Technology; Computer Integrated Manufacturing Systems (2); Computers in Industry; Ergonomics; Human Factors and Ergonomics In Manufacturing (3); International Journal of Applied Engineering Research; International Journal of Computer Integrated Manufacturing; International Journal of Industrial Ergonomics; International Journal of Production Research; Journal of Engineering Manufacture; Journal of Intelligent Manufacturing; Mechatronics (2); SAE Technical Papers; The International Journal of Human Factors in Manufacturing (5)	**23**	**0.40**	**19**	**0.61**	**4**	**0.15**
Book series Advances in Intelligent Systems and Computing, Applied Mechanics and Materials	**2**	**0.03**	**0**	**0.00**	**2**	**0.07**

Notes: 58 publications, 31 appeared before Industry 4.0 and 27 within Industry 4.0. Number in parentheses indicates the time a source appears in the sample.

4.0 according to our aforementioned understanding of the concept ‘anthropocentric production’. Studies are available from 1989 to May 2017. Without setting a limitation for the time, 1989 represents the starting point of scholarly discussion on anthropocentrism in production. Most research occurs in conference proceedings (57%). Particularly, anthropocentrism in the context of Industry 4.0 is overwhelmingly (78%) published in conference proceedings (see Table 2). Such a high rate indicates that the field is very much in a developing stage and either the exchange of concepts and ideas at conference level the publication of stable and settled findings at journal level is the rule.

As expected, the most publications on anthropocentrism in Industry 4.0 occurred in 2016, because the time of data collection took place in early 2017 (average publication year is 2012, Std. Dev. = 5.36). However, we found that, even if the average publication date of papers regarding anthropocentrism in traditional production systems is 1999 (Std. Dev. = 7.40), the interest in this topic is still present and we only recognised a slight decrease. Fig. 2 further presents the occurrence of papers per year.

4. Content analysis

In the following section, the identified body of literature sources is examined with special emphasis on content, methods and models. Firstly (Section 4.1), all sources of literature will be analysed which deal with traditional approaches prior to the introduction of Industry 4.0 and then (Section 4.2) the topics in the focus of Industry 4.0. The works are not examined according to chronological age, but rather divided into thematic cluster blocks to better understand the anthropocentric perspective and their related research fields before and after (or, better, within) Industry 4.0. In both Sections (4.1 and 4.2) the identified thematic clusters are organized with reference to a bidimensional framework related to the lifecycle (planning, execution, maintenance) and to the categorization of aids (physical, sensorial, cognitive). The classification according to the lifecycle chosen by the authors should help to make clear to the reader from the beginning, in which phase the respective concepts and methods can be applied (in the planning and design of a human-centred production system, in the execution of the same or for the maintenance of the system). By

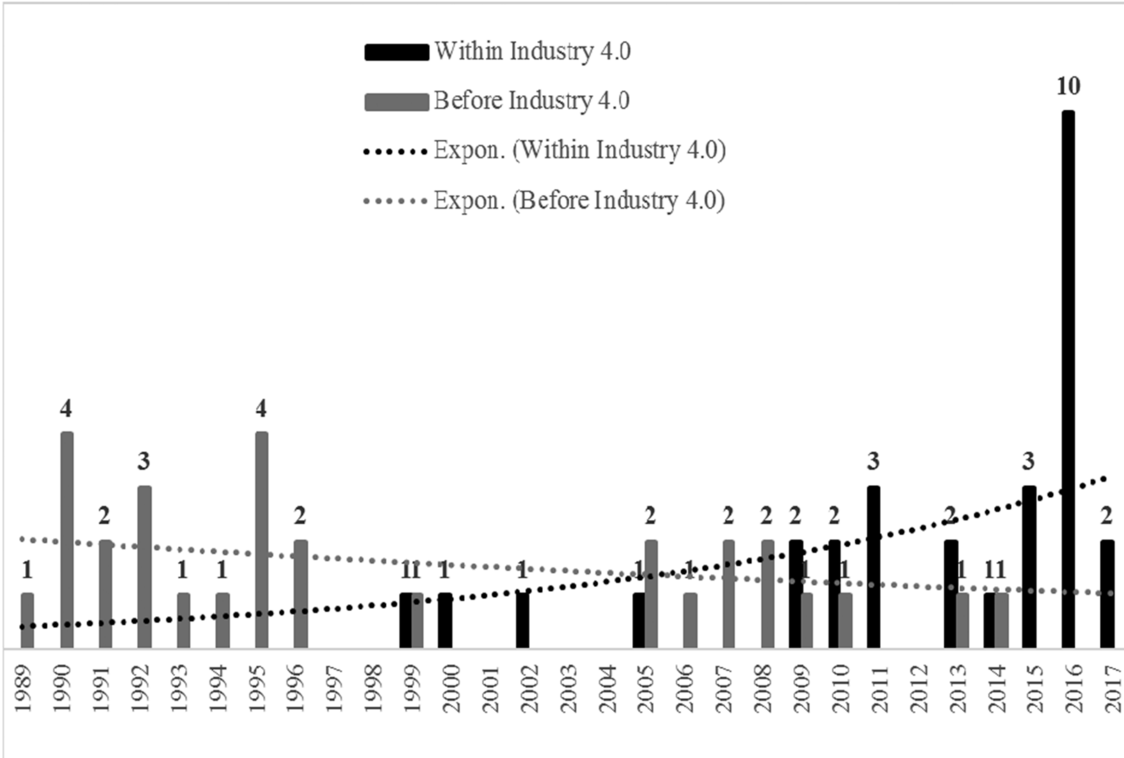

Fig. 2. Number and year of publication differentiated regarding publication before and within Industry 4.0. **Notes**: Before Industry 4.0 combines all traditional production approaches other than Industry 4.0.

applying this classification, it refers to the human-machine interface for the user of the aid and not to the human-machine interface for the operator, addressed by the designer. The categorization of the concepts and methods according to the type of aid originates from Romero et al. (2016), who in their work have subdivided them into the above-mentioned categories. Physical aid systems primarily serve to decrease the physical workload of a worker in production. Sensorial aid systems have the capacity and ability to acquire data from the environment, necessary for orientation and decision-making in the operator's daily work (Attwood, Deeb, & Danz-Reece, 2010, chap. 6.1). Cognitive aid systems are defined by the ability to support the mental tasks (e.g. perception, memory, reasoning, decision, motor response, etc.) needed for the job and under certain operational settings (Carrol, 1993). Within the framework of this categorization, technical support systems, methods or approaches as well as organizational mechanisms are assigned. As already mentioned above, a distinction is made as to whether these result in a reduction of the physical workload, support in the sense of data-based decision support or support for mental tasks.

4.1. Anthropocentric perspective before Industry 4.0

In the content analysis of research fields and anthropocentric perspectives before Industry 4.0 in traditional manufacturing approaches, four clusters could thus be identified (see Fig. 3). In the following, every cluster will be explained in more detail describing the main research topics.

4.1.1. Cluster 1 – Cognitive aid in planning of traditional production systems

Bohnhoff, Brandt, and Henning (1992) introduce the dual design approach for interdisciplinary human-centred systems with skill-based workplaces and group work in flat hierarchies. A parallel technology-based and working-process based design involving people at an early stage of development ensures a successful design. In their work, they define three main dimensions for APS: (a) the workplace, (b) group work and (c) organisational networks.

Schulze, Brau, Haasis, Weyrich, and Rhatje (2005) summarise the importance of computer aided planning tools (CAx) as success factors for human-centred design from a case study in the automotive industry focusing on relationship with suppliers. New CAx based production planning tools will significantly change not only the contemporary production process planner's work, but also the collaboration with suppliers. Success factors are an early integration in the design phase, parallel development of work method and user interface and interdisciplinary development teams.

Ergonomics plays a major role in APS. Therefore, workplace design needs to be adapted to the needs of the operator and developed in a participatory approach. Kidd (1990) presents a European perspective of human factors, whereby people are regarded as being equally, if not more, important as the technology. This means that the system designer has to design a manufacturing system in which the operator has the control, flexibility and choice of operating strategies, which will enable him to develop efficient working methods. For this reason, ergonomics play a major role in systems design. Kragt (1995) provides several case studies for the integration of human factors in the design and evaluation of manufacturing systems by applying ergonomics and human factors audits in the prototyping phase. Siva and Rajasekaran (2014) present the rapid entire body assessment (REBA) tool to design ergonomic work position in manufacturing. They analyse human activities based on a best-in-class human modelling arrangement. Based on scores from the REBA tool, the risk level and requirement of the design change of the work environment are addressed.

4.1.2. Cluster 2 – Physical aid for the execution of work in traditional production systems

Physical workload reduction can be achieved in different ways. One possibility is the introduction of job rotation in case of work stations with non-ergonomic or with physically demanding and stressful

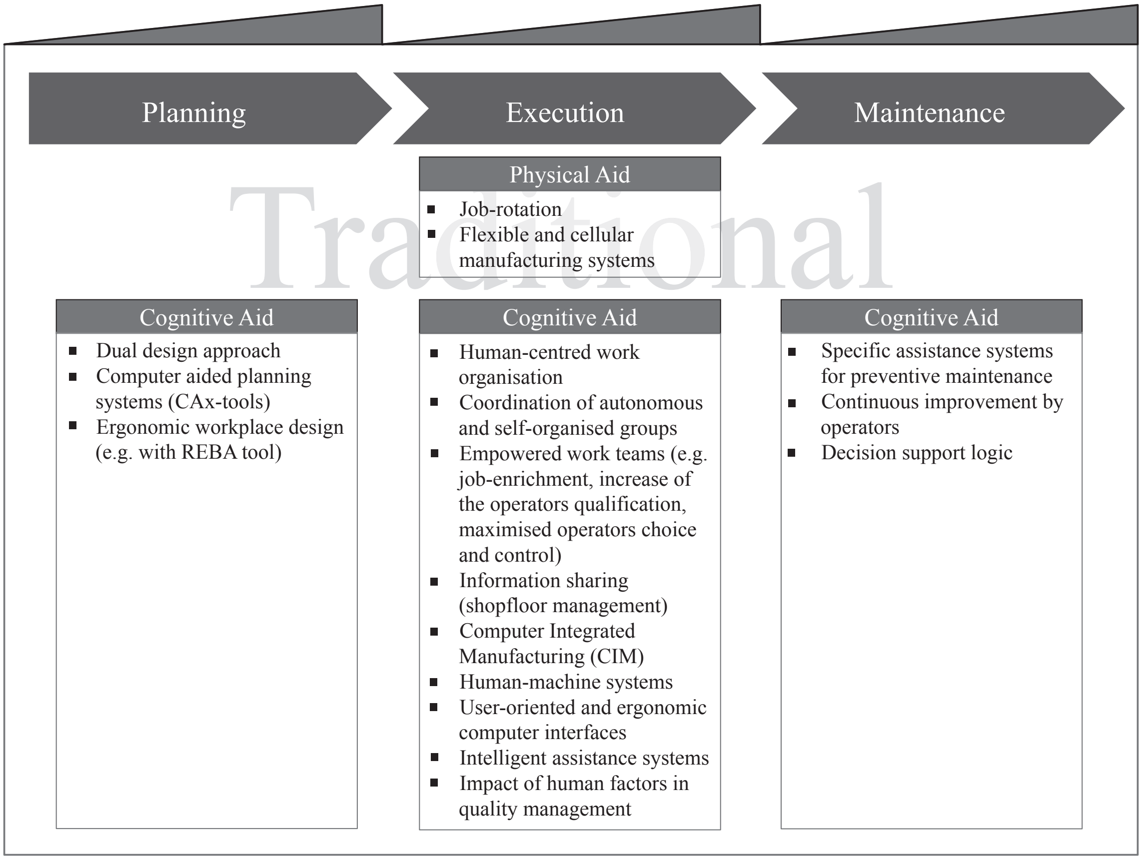

Fig. 3. Research clusters and topics in traditional APS.

activities. Černetič (2006) shows in several case studies measures for human-centred work organization, among them also job rotation as method for physical strain reduction.

Anthropocentric production cells have also been discussed in this research field. The earliest work is research by Slatter, Husband, Besant, and Ristic (1989) describing an approach for a human-centred design of advanced manufacturing systems with a special focus on flexible manufacturing systems (FMS) and human aspects. Through the introduction of cellular manufacturing, employees become multi-skilled, work in independent workgroups, take more responsibility for their work performance and coordinate their work with other cell-operators (Dawson, 1991). The human-centred combination of machines and human workforce in such production systems reduces not only the physical workload, where necessary and reasonable, but increases also operator wellbeing and variety of work (Michelini, 1992).

4.1.3. Cluster 3 – Cognitive aid for manufacturing execution in traditional production systems

Human centred work organisation seems to be one of the basic research fields for APS in traditional manufacturing, defining how organisation in manufacturing should be designed in order to gain from human experience and skills. Corbett (1990) is among the first who addresses human aspects in advanced manufacturing systems whereby the human controls the technology and not vice-versa. While traditional approaches tend to the deskilling of the human, human-centred technology allows to develop the skill of the user. In his work, the author aims to promote this approach, showing first practical applications in a case study. Hirsch, Hamacher, and Thoben (1992) reflect on human aspects in production management wherein coordination, communication in networks of groups as well as learning and experience of operators are the main elements. Further, they highlight human resource management, complexity of capabilities, holistic work design and informal organisations as key concepts for human centredness. Černetič (2006) justifies the development of human-centred work systems based on their cost-effectiveness and functionality. The author shows the results of nine case studies where measures for human-centred work organisation have been applied: autonomy, group work, job enlargement, job rotation, planning and quality control organised by operators and worker qualification.

Fan and Gassmann (1995) investigate the practicalities of human-centred approaches in a British manufacturing company. The research team recognised difficulties in overcoming traditional working practice and a need for improvement in communication, trust, sharing of information and team working skills. Mital and Pennathur (1999) argue in favour of a human-centred (anthropocentric) approach to modern manufacturing. Before such systems can lead to excellence in manufacturing, certain deficiencies need to be corrected, such as skill training and the management of large amounts of information by means of computers. Fujita, Kato, Watanabe, Tan, and Arai (2009) analyse the operator's mental strain induced by information support in cell production. According to the authors, information support provides a solution to improve operator's operation performance and to reduce his/her mental strain. Thus, in their study, the operator's performance is measured in terms of assembly errors when an information support system is introduced. Shishir (2010) presents the results of a change from conveyor-based assembly lines to human-centred work-cell-based systems to deal with fluctuations in demand. The implementation and support of a cell production system relies greatly on the development of work teams and reinforcement of individual skills as well as broadened multitasking. This aims at empowering work teams for the challenge of dealing with vertically enriched roles. Folgado, Henriques, and Peças (2012) analyse the impact of workers with different combinations of performance on an asynchronous and unbuffered assembly line. Based on different operator skills, their task times can vary significantly one from the other. If there is a worker with a worse performance than the others, the system output is significantly reduced. Therefore, training as well as the development of ergonomic and human-centred workplaces and assistance systems are important to overcome this effect.

With the third industrial revolution (computerisation), CIM introduced a new era in manufacturing through non-physical or digital assistance for the operator and product or production system designer. A great challenge of CIM was the design of human-computer interface and interaction. Hancke (1990) shows a sample application of human-centred design in man-machine and CIM systems. Also, Ainger (1990) discusses the application of human-centred CIM systems in production, shaping technology around people together with the organisation in which they operate and, thus, creating a balance between technology, organisation and people. While traditional approaches tend to minimise the role of the operator, human-centred CIM systems give the employee a central role. Husband (1990) proposes that human-centred factories consist of flexible production islands, which use both highly automated and worker-dependent equipment. The computer integration in a human-centred factory should take account of the existing skills of the operator, enable the operator to have a maximum knowledge of the entire production process, encourage communication and maximise operator choice and control. Harnor (1995) describes a production sequencing advisor concept in an anthropocentric manufacturing cell. Manufacturing cells usually have an agreed workload that enables the cell team to achieve their targets. The objective of the study is to utilise the skill of the users, such that a CIM-based multi-attribute ranking model advises the user on the most appropriate scheduling rule. Uden (1995) defines participatory design and joint application design to build human-centred CIM systems. In this approach, users and designers share the responsibility of the design and its implementation, which leads to a more user-oriented and ergonomic design of CIM systems. Yang and Lee (1996) argue that many CIM implementations were not successful because human factors were not considered. Analysing different user-interface systems, like workbenches or management information tables and human networking systems, they found that human aspects are important to achieve system optimisations, intelligent workers and flexible organisation. Eichener (1996) analysed the impact of technical standards on the diffusion of APS focused on skilled human labour instead of technology. As a result, technical standards of CIM interfaces affect the realisation of human-centred CIM systems positively and negatively. They have consequences for work organisation, working conditions and worker skills.

The introduction of hybrid or semi-automated systems in manufacturing and assembly created the need for the design of human-machine interfaces in systems where the operator collaborates or interacts with a machine. Martin, Kivinen, Rijnsdorp, Rodd, and Rouse (1991) propose the integration of human factors in human-machine systems. The social dimension of automation technology consists in defining the machines in relation to the human operator. They suggest a humanisation of technology identifying the division of functions between machine and worker, an ergonomic and user-friendly design of the human-machine interface and, finally, an appropriate organisational structure in order to enable autonomy, responsibility and self-supervision. Černetič and Blatnik (2005) present a computer-aided human-centred collaborative system supporting just-in time (JIT) delivery of components in manufacturing. The aim of their work is to improve the working efficiency and cost-effectiveness in a more flexible allocation of functions between humans and machines. Bernhardt, Surdilovic, Katschinski, and Schröer (2007) developed a concept for intelligent assist systems (IAS) in order to support the human worker instead of replacing him. Flexibility should not be achieved through fully automated assembly systems, but should instead support the better integration of human workers. Suksawat, Hiroyuki, and Tohru (2007) present a model of communication in anthropocentric cell manufacturing systems. The paper aims to realise a case study-based model for connecting the manufacturing unit, a human-oriented user interface and a management and control unit for human machine collaboration in cellular manufacturing. Zhang, Schmidt, Schlick, Reuth, and Luczak (2008) carried out a collective analysis of human-centred simulation approaches in advanced manufacturing systems. The simulation results show some important transitions of human factors from the conventional production cell to autonomous cells, which can support the decision-making. System performance could be increased in the sense of productivity and quality due to an ergonomic human-machine interface for process planning and control and computer-aided support and assistance.

One of the identified literature sources dealt with quality management and the impact of human factors. Mantura (2008) promotes the importance and the role of human factors in quality management. Human factors were exhibited in the manager and executor roles in quality management systems in enterprises as well as the roles of creators, producers and users (customers) in product life cycles. The author especially points to the tradeoff between human factors occurring in enterprises (owners, managers, designers, executors) and human factors occurring in an enterprise's environment (customers, suppliers, interested parties, social groups).

4.1.4. Cluster 4 – Cognitive aid for maintenance in traditional production systems

The human role in maintenance and service operation is crucial for a well working manufacturing company. Some of the literature sources especially suggest knowledge-based preventive maintenance as well as the development of specific assistance systems. Gude and Schmidt (1993) show an empirical investigation of knowledge requirements in preventive maintenance and their implications for the human-centred approach. An implication is that the shop-floor staff should be supported by assistance systems in performing preventive maintenance func-tions. In addition, Wu and Seddon (1994) propose an anthropocentric approach for knowledge-based preventive maintenance. The concept is based on a human-centred decision support log-ic and includes a detailed assessment of each breakdown and an active participation of opera-tors followed by continuous improvement actions.

4.2. Anthropocentric perspectives within Industry 4.0

In the content analysis of anthropocentric perspectives within Industry 4.0, a further six clusters could be identified (see Fig. 4). In the following, every cluster will be explained in more detail describing the main research topics.

4.2.1. Cluster 1 – Cognitive aid in planning of cyber-physical production systems

With the digital transformation in manufacturing production system planning also becomes more and more dominated by cognitive aid tools and digital assistance systems for ergonomics analysis as well as process planning. Chen, Xia, Lang, and Yao (2009) present a framework which considers human factors in an early stage of assembly process planning by taking into account ergonomic analysis in a virtual assembly system. Yang, Deines, Lauer, and Aurich (2011) present the concept of a human-centred virtual factory, where human-centred components, like ergonomics, collaboration and training, are taken into consideration during the product design as well as the factory and process planning phases. By using a noise investigation example, they showed how virtual-reality (VR) systems could be used for human-centred analysis, planning and reconfiguration of manufacturing systems. Santochi and Failli (2013) explain the term sustainable work as related to the increasing competitiveness in the global economy, resulting in increased worker stress. One of the presented fields of intervention to minimise the stress of a worker on the assembly line is introducing advanced ergonomics leveraged by new and emerging information technology assistance systems, like augmented- and virtual reality. In Romero, Noran, Stahre, Bernus, and Fast-Berglund (2015), the authors propose a

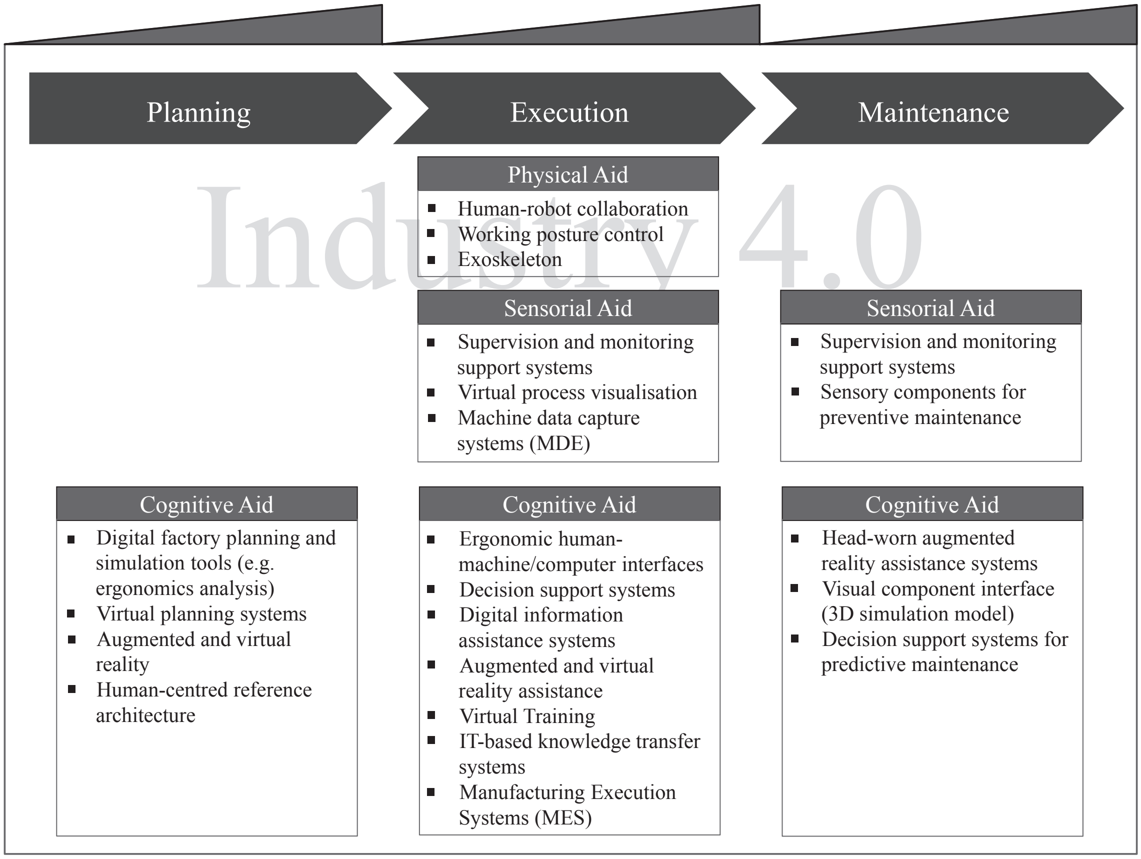

Fig. 4. Research clusters and topics in anthropocentric cyber-physical production systems.

human-centred reference architecture in order to guide and structure the design of next generation balanced automation systems with the aim to support ageing, disabled and apprentice operators in performing their work efficiently and comfortably. Assistance is provided in an intelligent, adaptive and dynamic way, which means workers are supported only when required. Hold, Ranz, Sihn, and Hummel (2009) describe an approach to design cyber physical assembly systems supported by technical (e.g. human-robot collaboration) and digital assistance systems (e.g. instruction, additional information, event-oriented information). By considering the capabilities/strengths of humans and machines, the approach supports the identification of tasks which can be supported by technical or digital assistance, leading to a cyber-physical assembly process design.

4.2.2. Cluster 2 – Physical aid for the execution of work in cyber-physical production systems

In the human-centred production of tomorrow, a major focus lies on facilitating the physical work for the operator. To achieve this goal, different research topics have emerged in recent years, such as the introduction of an exoskeleton or human machine/robot collaboration.

Tan and Arai (2010) quantitatively evaluated human-robot collaboration systems in cellular manufacturing. Based on a cable harness assembly case study, they performed a practical evaluation, considering (1) a manual setup and (2) a human-robot collaboration setup. The second one proved to have better direct performance measurements (in terms of reduced assembly duration and preventing of assembly errors). Considering the human factors, according to the feedback from the human operators, the human-robot collaboration was less tiring (due to the taking over of assembly tasks by the robot systems), but some operators experienced mental stress because of safety concerns due to a close collaboration with the robot system. Shen, Reinhart, and Tseng (2015) present a design approach for setting up work-cells with human-robot-coexistence enabling ergonomic workload distributions and considering the human safety. Unlike human-robot-collaboration, in human-robot-coexistence the worker and the robot share a common workspace, but not a common task. The design approach for human-robot-coexistence was tested experimentally by using a seat assembly work cell in the automotive industry.

Thomas et al. (2016) describe a design approach for human-robot-collaboration, which considers employees' personal anthropometric data. The demographic change within European countries has led to an increase of the mean age of its workforce population. As a result, a decline of the working population is predicted from 67% to 56% by 2060 (European Commission, 2012). Correspondingly, automation will increase in European manufacturing companies. Moreover, according to Thomas et al. (2016), flexible systems assisting the operator in assembly operations, which consider age-related physical work capacities (e.g. restrictions in movements) as well as personal capabilities and skills are required. (Nguyen, Bloch, & Kragt, 2016; Nguyen, Pilz, & Krüger, 2017) present an innovative assistance system called the working posture controller (WPC), which reduces work-related musculo-skeletal disorders (WMSDs). According to Nguyen, Pilz, and Krüger (2017), WMSDs can be considered as the major reasons for work absenteeism. The system consists of sensors monitoring and assessing the working posture of the operator, and an intelligent actuator system, which automatically adjusts the work piece pose, allowing the operator to adopt a natural working posture. However, they mention economic and legal challenges: (1) potential benefits are difficult to measure and (2) a continuous monitoring of workers could raise concerns in the field of privacy.

4.2.3. Cluster 3 – Sensorial aid for manufacturing execution in cyber-physical production systems

Sensorial aid in manufacturing execution consists mainly in data capturing, supervision and visual control systems using sensor data. Riera, Lambert, and Amat (1999) state that progress in the field of automation has been changing the operator's work. During normal running of production systems, the field of activity consists of supervision and, during abnormal running, the human operator has to take complex decisions to restore the proper functioning of the production system. Riera, Lambert, and Amat (1999) propose specifications for an advanced human centred supervisory system (AHCSS) used for monitoring and diagnosing manufacturing systems. According to Wittenberg (2002), modern production systems lead to an increasing degree of automation and the operator's tasks are more and more changing to supervision and control functions. Moreover, due to the increase of complexity of production systems, a user-centred process visualisation is increasingly important to guarantee effective monitoring and controlling by human operators. As such, Wittenberg (2002) presents a pictorial three-dimensional process visualisation concept (the virtual process visualisation), to bridge the gap between the operator and the production system.

4.2.4. Cluster 4 – Cognitive aid for manufacturing execution in cyber-physical production systems

In the content analysis, several approaches of cognitive assistance for manufacturing execution in CPPS were identified. First ergonomic human-machine interfaces are needed. The initial research in the area of human-machine interface has been expanded over time and, with the introduction of Industry 4.0, now includes research into an ergonomic interaction between human-machine, as well as between human-computer. Based on Cakmakci (2005), the effective utilisation of advanced manufacturing systems can be achieved by focusing on human factors in human-computer interfaces. The author analyses the technological issues of human-computer interfaces, which influence the performance of human factors in advanced manufacturing systems. According to Ohtsuka, Shibasato, and Kawaji (2009), the operator's skill affects directly the control effectiveness in a human-machine system. As a response, they present a compensation mechanism in human-machine systems, called "collaborator", with the aim to control the decision-making of human operators and reducing the time response between command and action. Weiss, Buchner, Tscheligi, and Fischer (2011) present a human-robot cooperative production system in the semi-conductor manufacturing industry. Moreover, they propose a wearable system, which is integrated in the operator's suite enabling the operator to remotely observe and control the robot's state. A next identified trend in cognitive assistance systems is the increase in so-called manufacturing execution systems (MES) and related functionalities for decentralised production planning and control. In Pirvu, Zamfirescu, and Gorecky (2016), an anthropocentric cyber-physical system (ACPS) is presented, wherein humans are not just interacting with a CPS, but they are active components of it. The paper presents an ACPS reference model, which is composed of physical, computational/cyber and human components highly interacting with each other and used as the basis for the design of distributed manufacturing control systems. The practical relevance of the ACPS is shown by the application to a manual assembly station (Pirvu et al., 2016) According to Nelles et al. (2016), "Industry 4.0 is a way to respond to the needs for successful application of technology with human-centred (semi)-automation". They present a system which supports the human in decision-making for production planning and control. The system acquires, analyses and aggregates information in real-time and proposes alternative operation choices, considering parameters like "cycle time", "timeliness", "inventory" and "capacity", to the human decision-maker. Another research field is shown by assistance systems for decision and interaction support. Djian, Azarmi, Azvine, Tsui, & Wobcke, 2000) present a working prototype called the intelligent assistant (IA) system, with the aim to enhance the cognitive capabilities of humans. The supporting tasks consist of time, information and communication management. Söffker, Flesch, Fu, Hasselberg, and Langer (2011) present the concept of human-process-interaction (HPI) which describes the interaction between human operators and the process to be accomplished in order to develop sophisticated assistance and supervision systems in complex environments. They describe how the framework could be applied to an industrial application scenario consisting of a semi-automated moulding process, whereby the operator is decoupled physically from the direct molding steps, but his expertise is integrated in the process. Pacaux-Lemoine, Trentesaux, and Rey (2016) present an assistance system to support humans in supervising and controlling an artificial self-organising manufacturing control system. Furthermore, they investigate the risks associated with the increasing complexity of intelligent manufacturing systems and, especially, the risk connected of removing the human from the control loop (Pacaux-Lemoine, Trentesaux, & Rey, 2016). Further, knowledge-based assistance systems support the operator in their work. According to Gorecky, Mura, and Arlt (2013), in the factory of the future the worker will be an active consumer and provider of information. By using the context of final assembly in the automotive industry (where the product complexity increases due to the definition of variants), they show two innovative examples for knowledge-delivery and skill transfer systems. While other assistance systems deal with augmented and virtual reality technology, Paelke (2014) presents an augmented reality assistance system, which guides the user in picking and assembly operations. According to the author, "augmented reality can support workers in the increasingly flexible and data rich environment of future smart factories" by providing a natural user interface (NUI). Paelke (2014) presents a demonstration system whereby the operator uses a head-worn display, which displays stereoscopic 3D graphics and guides the user for picking and assembly operations. The demonstration system is based on Lego bricks and the information about assembly instructions is contained in the RFID-label of the workpiece-carrier feeding the assembly station. Rauh, Zsebedits, Tamplon, Bolch, and Meixner (2015) present an assistance system running on the head-worn display (HWD) – Google Glasses and applied experimentally during the calibration process of the driver assistance system testing bay of the Audi A8 production line in Neckarsulm, Germany. By using the HWD-device, the operator receives the needed information and is able to document the executed test steps without interrupting the work flow. According to the authors, the HWD device optimises the work and training process. In Gorecky, Kamis, and Mura (2017), a virtual training system is presented. The system and methodology were successfully tested by two automotive case studies in training for learning new assembly operations. According to Gorecky et al. (2017), "human operators are acknowledged as the most flexible parts in the production system being maximally adaptive to the more and more challenging work environment."

4.2.5. Cluster 5 – Sensorial aid for maintenance in cyber-physical production systems

Wittenberg (2016) describes the changing role of operators working on the line. In the Industry 4.0 era, machines become more intelligent and undertake more and more tasks from the operator. As a result, the focus of the operator's action field is shifted to monitoring and supervising tasks. Moreover, due to the fact that machines and production lines become even more complicated, the operator needs supporting systems for performing maintenance operations efficiently and effectively. Wittenberg (2016) present an application of augmented reality to diagnose PLC-modules by using tablets and data glasses.

4.2.6. Cluster 6 – Cognitive aid for maintenance in cyber-physical production systems

In Vathoopan, Brandenbourder, and Zoitl (2016), a human-centred corrective maintenance methodology for mechatronic components is presented. Here, the human undertakes the corrective maintenance action, supported by a CPS. The CPS consists of a 3D-simulation, which runs in real-time parallel to the real component and details its basic working principles. Once a system deviation is identified, a skilled or unskilled workforce is supported by providing a visual interface to the component (skilled debugger) or by providing error classifications and debugging recipes (unskilled debugger).

5. Discussion

The first research question to answer concerns the anthropocentric perspective of production before and within Industry 4.0. Our results clearly indicate that the period before Industry 4.0 was significantly shaped by a change from a technology-oriented design of production systems towards a human-centred approach. Movements such as the human-oriented lean production concepts, like cellular manufacturing, and the era of CIM with its challenge to design and implement human-machine and human computer systems, were mainly attempts to integrate the human operator in a socially sustainable way into production. Other fields of interest in the anthropocentric perspective of production before Industry 4.0 are ergonomics, preventive maintenance and quality management.

The period after or within the introduction of Industry 4.0 shows a transformation of physical and cognitive aid systems. We have also identified the development of so-called sensorial aid systems. While data used to play a lesser role in the past, more and more intelligent sensors are now being integrated into machines and products in order to capture as much data as possible (or necessary) and to be able to evaluate and use it for optimization purposes. Our research further demonstrates that especially sensor-based and cognitive assistance systems have changed production with the introduction of Industry 4.0 and will continue to change it for at least the near future. With a series of new possibilities for diagnosis and real-time intervention in the production system, new potentials may emerge for an increased productivity and a higher quality and reliability.

The second research question was to compare the two perspectives, analysing the transformation of research fields in anthropocentric production with the introduction of Industry 4.0. In order to answer to this question, the transformation of the research topics before and within Industry 4.0 is illustrated and examined in Fig. 5.

This figure shows the development of the described clusters with emphasis on similarities, differences and their transformation and trends, which we further discuss regarding two perspectives.

Both in traditional manufacturing and in Industry 4.0, the human-centred planning of manufacturing systems plays an important role. However, we found that the design models like dual design are now consolidated and have also been adopted and implemented in industrial practice. Nowadays, it is common to design a workplace according to the requirements of the operator. However, new methods of digital factory planning also open completely new possibilities for planning a workstation already human-centred from the virtual scratch. We can identify an evolution from computer-aided planning tools to an era of digital factory planning tools. Such modern digital planning tools will be enriched in the future by an increased use of AR planning systems. In planning of manufacturing systems, we observe multiple efforts to make workplaces also more user-friendly and healthy. Particularly, factory planning and simulation software systems (e.g. Jack of Siemens) are used with the purpose to test, by means of VR or AR technologies, the efficiency and functionality of workplace designs.

While, decades ago, topics such as job rotation, flexible manufacturing and cellular manufacturing were still much discussed, the interest in scientific discussions has diminished considerably over the past few years. The propagated change from the monotonous assembly line to a flexible cell production is a consolidated and already accepted topic in industry. The advantages of cell fabrication still apply, but there is no longer any interest in a scientific deepening. The flexibility in production has been discussed over the past few years with regard to reconfigurable, changeable and agile production systems, whereby a human-centred work organisation has also become the standard here. In the future research to decrease physical effort of workers will concentrate on an increase of (smart) automation, the integration of human-robot collaboration with safe lightweight 'cobots' (collaborative robots) as well as wearable machines and robots (e.g. the use of exoskeletons).

Sensorial aid systems are launching a kind of revolution in production. It is not that no data was collected from production in the past, but this can be done now in a completely new quality with smart sensors and sensor networks. Data is the gold of the future used for supervision and monitoring systems. Thus, sensors and machine data capturing systems are increasingly being introduced for the generation and acquisition of data.

Cognitive systems are those that are concerned with supporting the cognitive abilities of the worker and should help him/her to perform coordinating/dispositive tasks or monitoring tasks or even to make decisions. In cognitive aid for manufacturing execution in traditional production, great attention was paid to the training and qualification of the worker. This will be maintained as an important component in the smart factory. However, the worker receives completely new types of virtual training by means of technologies of virtual reality, whereby his learning ability should be increased and accelerated. Two decades ago, CIM was an internationally discussed research subject. The goals, such as computer-assisted production or decentralised production control, set at that time have become even more important today, which is why the research intensity has increased significantly in the meantime. Computer integration with the now established CAx technologies and systems has already been consolidated, but new systems and concepts like MES have emerged, which also require much development work on the research side. Within the framework of production system planning, CAx technologies have now been integrated into the digital factory concept and further developed. In the area of production planning and control, MES systems and other intelligent assistance systems or smart shop floor systems are used. The integration of human aspects in the field of quality management was previously only inadequately possible. The focus in the area of quality management has become even more pronounced. The current development of MES systems shows a strong orientation towards quality management in most cases. For instance, sample checks or test plans can be carried out via MES. Most MES systems are now offered together with a separate module for quality management, which is why the topic is currently of increasing interest.

Our results also indicate that human machine systems are just as important as in the past, if not even more so, since not only the interface to the machine is important, but also the robot or even the computer in the form of user interfaces. A new challenge is the ergonomic design of user interfaces for software as well as for control systems for machines, due to the increase of software and machine control systems in manufacturing. In the area of the human-robot interaction, there are completely new possibilities for collaboration between human beings and machines, which would not have been possible previously due to safety concerns. Human machine interfaces are still a research topic. They are needed to collect machine data and to display these to the operator in an ergonomic and effective way. Today, various methods and technologies (e.g. eye tracking software) are also being researched to develop ergonomic user interfaces making them even more appealing and intuitive.

Sensor assistance systems are also revolutionizing maintenance. In the past, preventive maintenance was very rudimentary, trying to optimise the maintenance by analysing historical downtimes by means of preventive measures. In the meantime, data can be collected through smart sensors and sensor networks. This collected data can be analysed and evaluated for these purposes by means of sensorial aid systems. The monitoring systems developed in this way enable a complete digitalisation in maintenance planning and scheduling. Through the application of artificial intelligence, preventive maintenance systems can be developed to predictive maintenance systems.

In the past mainly methods from lean theory were used for preventive maintenance. New additions in the field of cognitive aid

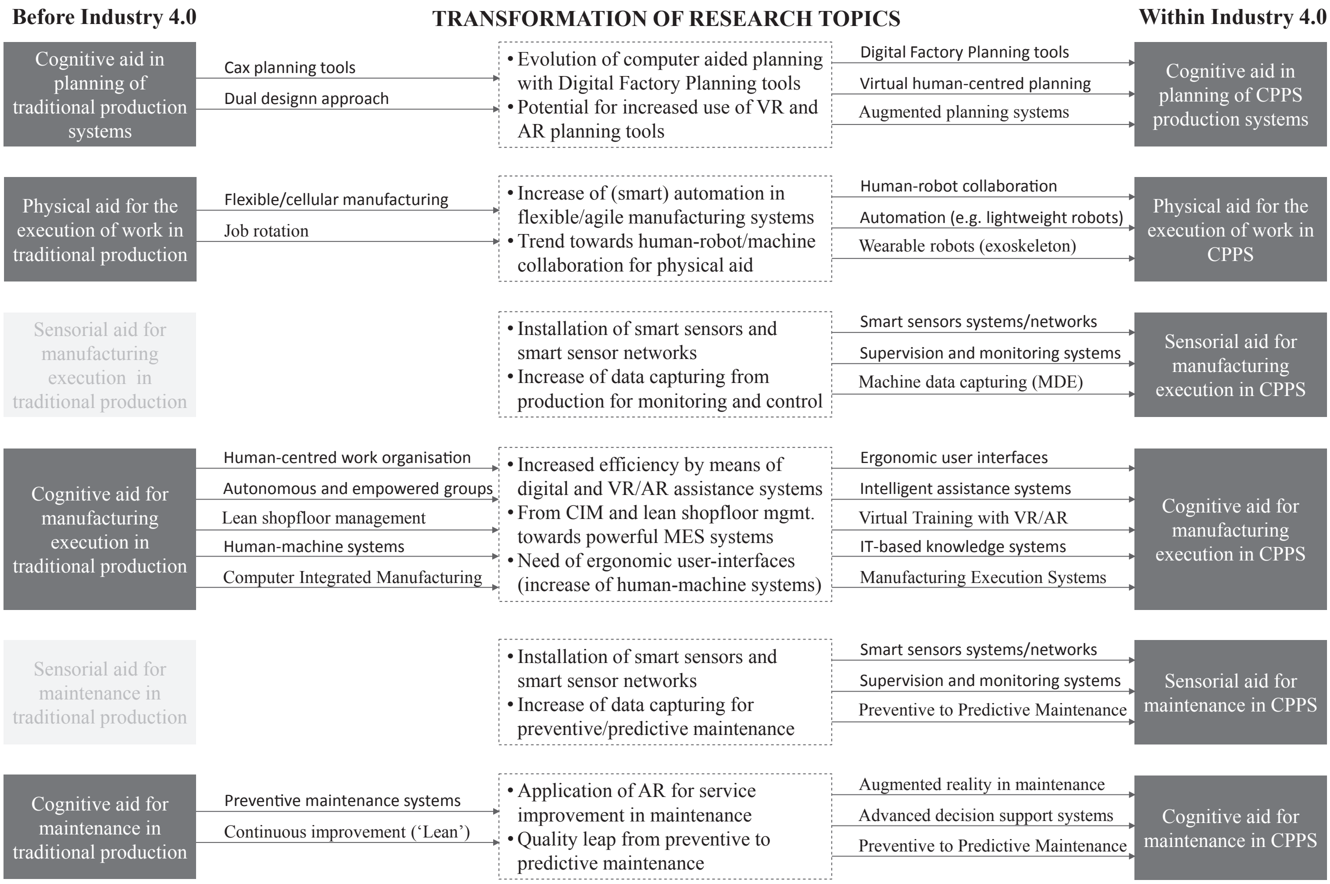

Fig. 5. Transformation of research topics.

systems for maintenance are technologies such as augmented reality, which means that the operator has a digital support for the execution of non-repetitive maintenance tasks. In addition, advanced and intelligent decision systems support the decision-making process of maintenance staff.

Overall, the comparison of the identified clusters shows that many new helpers and assistance systems for the future operator are currently in development. According to Romero et al. (2016) these can be classified into physical aid systems (i.e. systems that support the worker in the physiological work), sensorial aid systems (those systems that record data and make it available to the operator) and cognitive systems.

As the bulk of the literature on Industry 4.0 at this stage is mostly of a theoretical nature, there is a lack of data and practical experiences about what happens during and after the implementation of all the previously discussed Industry 4.0 research topics with regard to the people involved, specifically. The measures that have been discussed so far may therefore appear more 'rosy' now than they might be in a few years' time. In view of the uncertainties in the future development of Industry 4.0 as well as the unknown outcome of the new technologies and the human-machine interactions, the authors would therefore also like to draw attention to possible risks associated with this development. Therefore, the measures discussed so far may well be less 'rosy' than they might be in several years. Potential risks can lie both in a (non-physical, but cognitive) overload of workers (Dombrowski & Wagner, 2014) and in the fact that the development of Industry 4.0 is being driven forward more quickly than training and education institutes are able to adapt the qualification profile of existing and future workers at all (Benešová & Tupa, 2017). This is accompanied by the fear, as is currently much discussed (Arntz, Gregory, & Zierahn, 2016; Bonekamp & Sure, 2015), that increasing digitisation in industry will result in a large wave of unemployment. For this reason, the authors also point out the importance and significance that researchers are increasingly addressing these issues of social sustainability in their research.

6. Conclusion and outlook

In this paper, a SLR regarding anthropocentrism in production before and within Industry 4.0 is presented. To answer the first research question, different clusters regarding the anthropocentric perspective of production before and after or better within Industry 4.0 were identified based on a content analysis of references from the SLR (see Figs. 3 and 4).

The following structure was elaborated. By setting the boundaries to the operator and its environment as the production system, a structuring in (1) planning of the production system (technical and organisational design), (2) execution of the production system and (3) maintenance of the production system, was performed. Moreover, the following clustering was applied: (1) Cognitive aid in the planning phase of a production system; (2) physical aid in the execution phase; (3) sensorial aid in the execution phase; (4) cognitive aid in the execution phase; (5) sensorial aid in the maintenance phase; and (6) cognitive aid in the maintenance phase.

An analysis of the transformation of research fields in anthropocentric production following the arrival of Industry 4.0 was performed. As such, many new helpers and assistance systems for the Operator 4.0 are currently under development. According to the presented research, most efforts have been invested in the field of cognitive aid for the execution of production systems. Here, the worker is afforded completely new possibilities of virtual training by means of virtual reality technologies, whereby his learning curve can be drastically improved. Furthermore, the cognitive aid in the planning phase of production

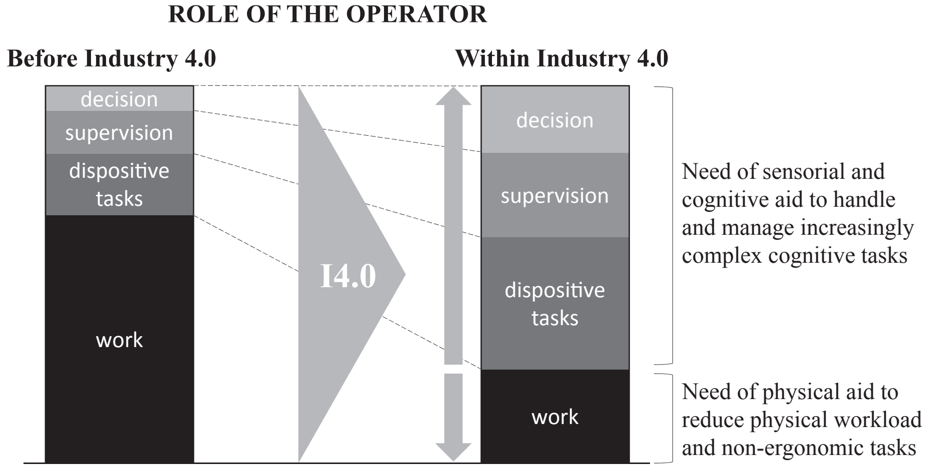

Fig. 6. Change in the role of the operator.

systems have been of interest, especially the digital factory planning, which opens up new possibilities for planning a human-centred workstation from virtual scratch. Regarding the tasks and the role of the operator in future factories, an increased share of complex cognitive tasks is predicted. Here, dispositive tasks to coordinate or organise production resources, as well as the control and monitoring of complex production systems will increase. Human operators will be a central part of future production systems, due to their cognitive abilities such as coordination, supervision and decision-making. To achieve this, the worker will need more and more data in the future. For this reason, sensorial aid systems will play an important role in data acquisition in the future.

Future research effort should be invested in the further development of assistance systems in the field of cognitive- and sensorial aid. The human or the operator is still, and even more so, at the centre of the production system. Through his cognitive abilities, which cannot be replaced by a machine, the operator remains necessary for industrial production (Romero et al., 2016). However, his task profile will change significantly in the next years. Fig. 6 shows, in a qualitative representation, how the tasks have and will be changed in future.

Years ago, the operator had mainly to carry out muscle work in the form of physical work on the product. This share of physical work will continue to fall and reach a minimum in future production systems (Romero et al., 2016). This requires an increased demand for physical aid systems and (intelligent) automation (Romero et al., 2016). On the other hand, the share of dispositive work to coordinate or organise material or other production resources increases (Gorecky et al., 2014). Another very important task is the control and monitoring, as well as decision-making, in case of uncertainties in production. In order to meet this new challenge, the human resources department has to train many more qualified staff and introduce support systems (Gorecky et al., 2013). The assistance systems mentioned here mainly concern sensorial and cognitive aid systems in order to be able to support the operator accordingly (Romero et al., 2016). Anthropocentrism in production definitely gains relevance in future smart factories. Future factories will be dominated by cyber-physical production systems with more intelligent automation than in traditional manufacturing systems (Romero et al., 2015). Even though such production systems become smarter and implement self-diagnosis, the cognitive skills of operators remain irreplaceable and are more in demand than ever before. Thus, the production system will be designed in order to facilitate the physical work in an ergonomic way and to assist the operator in complex or dispositive tasks like coordination, supervision and decision-making. The operator is no longer important because of his muscular strength, but rather because of his abilities, experience and senses.

Considering the research field of sensorial aid, much research has been performed regarding industrial practice; however, in the area of cognitive aid, a variety of application scenarios still exist, especially in the field of self-learning systems. Another future research area exists in the field of balancing the workload of the Operator 4.0. Despite the increasing support of a cognitive- and sensorial aiding system for coordination, monitoring and decision- making processes, an increased Operator 4.0 workload relies on learning how to use such sophisticated systems. As such, research in the field of training is needed, which challenges technical colleges, high schools and companies to prepare existing, as well as to qualify new operators in the factory of the future. In addition, the demographic change as well as the increasing immigration phenomenon pose further constraints, which could be compensated by anthropocentric cyber physical production systems.

Further research is also needed to better understand the effects of Industry 4.0 in its practical implementation with regard to the people involved, specifically. This is particularly important to transform SME companies into smart factories in symbiosis with the development and change of work and the necessary qualification profiles of people working in future smart factories.

Declaration of interest

The authors disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work.

Acknowledgment

This work was supported by the Open Access Publishing Fund provided by the Free University of Bozen-Bolzano.

References

Arntz, M., Gregory, T., & Zierahn, U. (2016). The risk of automation for jobs in OECD countries: A comparative analysis. *OECD social, employment and migration working papers: Vol. 189*Paris: OECD Publishing. https://doi.org/10.1787/5jlz9h56dvq7-en.

Attwood, D., Deeb, J., & Danz-Reece, M. (2010). Personal actors. In M. Tooley (Ed.). *Design engineering manual* (pp. 234–247). Butterworth-Heinemann.

European Commission (Ed.). (2012). *The 2012 ageing report*. Brussels: European Union.

Ainger, A. W. S. (1990). *Aspects of an experimental industrial application of a human-centered CIM system. Human factor in CIM, IEE colloquium on*. IET.

Armstrong, D., Gosling, A., Weinman, J., & Marteau, T. (1997). The place of inter-rater reliability in qualitative research: An empirical study. *Sociology, 31*(3), 597–606.

Benders, J., Haan, J. A. C. D., & Bennett, D. (1995). *The symbiosis of work and technology*. London: Taylor and Francis.

Benešová, A., & Tupa, J. (2017). Requirements for education and qualification of people in industry 4.0. *Procedia Manufacturing, 11*, 2195–2202.

Bernhardt, R., Surdilovic, D., Katschinski, V., & Schröer, K. (2007). Flexible assembly systems through workplace-sharing and time-sharing human-machine cooperation. *IFAC Proceedings, 40*(3), 247–251.

Bohnhoff, A., Brandt, D., & Henning, K. (1992). The dual design approach as a tool for the in-terdisciplinary design of human-centered systems. *International Journal of Human Factors in Manufacturing, 2*(3), 289–301.

Bonekamp, L., & Sure, M. (2015). Consequences of Industry 4.0 on human labour and work organisation. *Journal of Business and Media Psychology, 6*(1), 33–40.

Booth, A., Papaioannou, D., & Sutton, A. (2012). *Systematic approaches to a successful literature review*. London: SAGE.

Cakmakci, M. (2005). Relationship between performance of human factors and man-machine interaction in advanced manufacturing systems. *Proceedings of the 35th international conference on computers and industrial engineering* (pp. 351–356). ICC and IE.

Carrol, J. B. (1993). *Human cognitive abilities*. Cambridge: Cambridge University Press.

Černetič, J. (2006). Some more evidence for justifying human-centred systems. *Automated Systems Based on Human Skill and Knowledge, 9*(1), 97–102.

Černetič, J., & Blatnik, R. (2005). Human-centred collaborative system supporting it delivery in manufacturing. *IFAC Proceedings, 38*(1), 66–71.

Chen, P., Xia, P. J., Lang, Y. D., & Yao, Y. X. (2009). A human-centered virtual assembly system. *Applied Mechanics and Materials, 16–19*, 796–800.

Connolly, T. M., Boyle, E. A., MacArthur, E., Hainey, T., & Boyle, J. M. (2012). A systematic literature review of empirical evidence on computer games and serious games. *Computers & Education, 59*(2), 661–686.

Cooley, M. (1987). Human centred systems: An urgent problem for systems designers. *Ai & Society, 2*(1), 47–61.

Corbett, J. M. (1990). Human centred advanced manufacturing systems: From rhetoric to reality. *International Journal of Industrial Ergonomics, 5*(1), 83–90.

Dawson, P. (1991). From machine-centered to human-centered manufacture. *International Journal of Human Factors in Manufacturing, 1*(4), 327–338.

Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In D. A. Buchanan, & A. Bryman (Eds.). *The SAGE Handbook of Organizational Research Methods* (pp. 671–689). London: SAGE Publications.

Djian, D., Azarmi, N., Azvine, B., Tsui, K. C., & Wobcke, W. (2000). Towards human-centred intelligent systems: The intelligent assistant. *BT Technology Journal, 18*(1), 91–92.

Dombrowski, U., & Wagner, T. (2014). Mental strain as field of action in the 4th industrial revolution. *Procedia CIRP, 17*, 100–105.

Eichener, V. (1996). The impact of technical standards on the diffusion of anthropocentric production systems. *International Journal of Human Factors in Manufacturing, 6*(2), 131–145.

Epley, N., Waytz, A., & Cacioppo, J. T. (2007). On seeing human: A three-factor theory of anthropomorphism. *Psychological Review, 114*(4), 864–886.

Fan, I. S., & Gassmann, R. (1995). Study of the practicalities of human centred implementation in a British manufacturing company. *Computer Integrated Manufacturing Systems, 8*(2), 151–154.

Folgado, R., Henriques, E., & Peças, P. (2012). Impact of workers with different task times on the performance of an asynchronous assembly line. *Proceedings of the 37th international MATADOR conference* (pp. 235). .

Fujita, M., Kato, R., Watanabe, K., Tan, J. T. C., & Arai, T. (2009). Operators' mental strain induced by information support in cell production. *Assembly and manufacturing, 2009. ISAM 2009. IEEE international symposium on* (pp. 196–201). IEEE.

Genaidy, A. M., & Karwowski, W. (2003). Human performance in lean production environment: Critical assessment and research framework. *Human Factors and Ergonomics in Manufacturing & Service Industries, 13*(4), 317–330.

Gorecky, D., Kamis, M., & Mura, K. (2017). Introduction and establishment of virtual training in the factory of the future. *International Journal of Computer Integrated Manufacturing, 30*(1), 182–190.

Gorecky, D., Mura, K., & Arlt, F. (2013). A vision on training and knowledge sharing applications in future factories. *IFAC Proceedings, 46*(14), 90–97.

Gorecky, D., Schmitt, M., Loskyll, M., & Zuhlke, D. (2014). Human-machine-interaction in the industry 4.0 era. *2014 12th IEEE International conference on industrial informatics (INDIN)* (pp. 289–294). IEEE.

Gude, D., & Schmidt, K. H. (1993). Preventive maintenance of advanced manufacturing systems: A laboratory experiment and its implications for the human-centered approach. *International Journal of Human Factors in Manufacturing, 3*(4), 335–350.

Hancke, T. (1990). Sample application of the human-centered design philosophy in a CIM system. In Human factor in CIM, IEE colloquium on (4–1).

Harnor, R. (1995). A production sequencing advisor in an anthropocentric manufacturing cell. In Human centred automation, IEE colloquium on.

Hirsch, B. E., Hamacher, B., & Thoben, K. D. (1992). Human aspects in production management. *Computers in Industry, 19*(1), 65–77.

Hold, P., Ranz, F., Sihn, W., & Hummel, V. (2009). Planning operator support in cyber-physical assembly systems. *IFAC-PapersOnLine, 49*(32), 60–65.

Husband, T. M. (1990). Human-centered technology for CIM systems. *Proceedings of manufacturing international* (pp. 15–19). ASME.

Kagermann, H., Wahlster, W., & Helbig, J. (2013). *Umsetzungsempfehlungen für das Zukunftspro-jekt Industrie 4.0: Abschlussbericht des Arbeitskreises Industrie 4.0. Frankfurt: acatech –*. Deutsche Akademie der Technikwissenschaften.

Kidd, P. T. (1990). Human factors in CIM: A European perspective. In Human factor in CIM, IEE colloquium on (2–1).

Kitchenham, B., & Charters, S. (2007). Guidelines for performing systematic literature reviews in software engineering. Keele: Tech. Rep. EBSE Technical Report EBSE-2007-01.

Kitchenham, B., Pretorius, R., Budgen, D., Pearl Brereton, O., Turner, M., Niazi, M., & Linkman, S. (2010). Systematic literature reviews in software engineering: A tertiary study. *Information and Software Technology, 52*(8), 792–805.

Kovács, I., & Moniz, A. B. (1994). Trends for the development of anthropocentric production systems in small less industrialised countries: The case of Portugal, MPRA Paper No. 6551, Paper presented at the European Workshop in Human Centred Systems, Brighton (UK).

Kovács, I., & Moniz, A. B. (2013). Issues on the anthropocentric production systems. In L. Camarinha-Matos, & H. Afsarmanesh (Eds.). *Balanced automation systems. Architectures and design methods* (pp. 131–140). New York, NY: Springer.

Kragt, H. (1995). Enhancing industrial performance: Experiences of integrating the human factor. *Ergonomics, 38*(8), 1674–1685.

Mantura, W. (2008). Human factors in quality management. Industries. *Human Factors and Ergonomics in Manufacturing & Service Industries, 18*(5), 565–579.

Martin, T., Kivinen, J., Rijnsdorp, J. E., Rodd, M. G., & Rouse, W. B. (1991). Appropriate automation—Integrating technical, human, organizational, economic and cultural factors. *Automatica, 27*(6), 901–917.

Michelini, R. C. (1992). Decision-anthropocentic manifold for flexible-specialization manufacturing. In 1992 Japan – USA symposium on flexible automation (Part 1) (pp. 467–474).

Mital, A., & Pennathur, A. (1999). Human centered manufacturing: A necessity for enhancing productivity and competitiveness. SAE technical paper, no. 1999-01-1605.

Mukhopadhyay, P., & Subhas, C. (Eds.). (2014). *Internet of things: Challenges and opportunities. Smart Sensors, Measurement and Instrumentation*. Cham: Springer.

Mulrow, C. D. (1994). Systematic reviews: Rationale for systematic reviews. *British Medical Journal, 309*(6954), 597–599.

Nelles, J., Kuz, S., Mertens, A., & Schlick, C. M. (2016). Human-centered design of assistance systems for production planning and control: The role of the human in industry 4.0. *Industrial Technology (ICIT), 2016 IEEE International conference on* (pp. 2099–2104). .

Nguyen, T. D., Bloch, C., & Kragt, H. (2016). The working posture controller: Automated adaptation of the work piece pose to enable a natural working posture. *Procedia CIRP, 44*, 14–19.

Nguyen, T. D., Pilz, C., & Krüger, J. (2017). The working posture controller-automated assessment and optimisation of the working posture during the process. In Advances in intelligent systems and computing (pp. 93–105).

Ohtsuka, H., Shibasato, K., & Kawaji, S. (2009). Experimental study of collaborater in human–machine system. *Mechatronics, 14*(9), 450–456.

Ortenblad, A. (2010). Odd couples or perfect matches?: On the development of management knowledge packaged in the form of labels. *Management Learning, 41*(4), 443–452.

Pacaux-Lemoine, M. P., Trentesaux, D., & Rey, G. Z. (2016). Human-machine cooperation to design Intelligent Manufacturing Systems. In Industrial electronics society, IECON 2016, 42nd annual conference of the IEEE (pp. 5904–5909).

Paelke, V. (2014). Augmented reality in the smart factory: Supporting workers in an industry 4.0 environment. *Emerging technology and factory automation (ETFA), annual conference of the IEEE* (pp. 1–4). .

Petticrew, M., & Roberts, H. (2006). *Systematic reviews in the social sciences: A practical guide*. Oxford: Blackwell.

Piore, M., & Sabel, C. F. (1984). *The second industrial divide: Possibilities for prosperity*. New York: Basic Books.

Pirvu, B. C., Zamfirescu, C. B., & Gorecky, D. (2016). Engineering insights from an anthropocentric cyber-physical system: A case study for an assembly station. *Mechatronics, 45*(1), 147–159.

Purser, R. E., Park, C., & Montuori, A. (1995). Limits to anthropocentrism: Toward an ecocentric organization paradigm? *Academy of Management Review, 20*(4), 1053–1089.

Rauch, E., Seidenstricker, S., Dallasega, P., & Hämmerl, R. (2016). Collaborative cloud manufacturing: Design of business model innovations enabled by cyberphysical systems in distributed manufacturing systems. *Journal of Engineering* (Article ID 1308639).

Rauh, S., Zsebedits, D., Tamplon, E., Bolch, S., & Meixner, G. (2015). Using Google Glass for mobile maintenance and calibration tasks in the AUDI A8 production line. In Emerging technologies & factory automation (ETFA), 2015 IEEE 20th conference (pp. 1–4).

Rauner, F., Rasmussen, L., & Corbett, J. M. (1988). The social shaping of technology and work: Human centred CIM systems. *Ai & Society, 1*(1), 37–46.

Riera, B., Lambert, M., & Amat, A. L. (1999). Specifications for an advanced human centered supervisory system. In Systems, man, and cybernetics, 1999 IEEE international conference on (pp. 780–785).

Romero, D., Bernus, P., Noran, O., Stahre, J., & Fast-Berglund, Å. (2016). The operator 4.0: Human cyber-physical systems and adaptive automation towards human-automation symbiosis work systems. In I. Nääs (Ed.). *Advances in production management systems. Initiatives for a sustainable world. APMS 2016. IFIP Advances in Information and Communication Technology* (pp. 1–11). Springer.

Romero, D., Noran, O., Stahre, J., Bernus, P., & Fast-Berglund, Å. (2015). Towards a human-centered reference architecture for next generation balanced automation systems: Human-automation symbiosis. *Advances in production management systems, IFIP international conference on* (pp. 556–566). Springer.

Rosenbrock, H. H. (1990). *Machines with a purpose*. Oxford: Oxford University Press.

Santochi, M., & Failli, F. (2013). *Sustainable work for human centred manufacturing*. London: Taylor & Francis.

Schulze, H., Brau, H., Haasis, S., Weyrich, M., & Rhatje, T. (2005). Human-Centered design of engineering applications: Success factors from a case study in the automotive industry. *Human Factors and Ergonomics in Manufacturing & Service Industries, 15*(4), 421–443.

Shen, Y., Reinhart, G., & Tseng, M. M. (2015). A design approach for incorporating task coordination for human-robot-coexistence within assembly systems. In Systems conference (SysCon), 9th annual IEEE international (pp. 426–431).

Shishir, B. N. (2010). Changing from conveyor to work-cell-based systems to deal with fluctua-tions in demand. *Journal of Engineering Manufacture, 224*(1), 169–176.

Siva, R., & Rajasekaran, R. (2014). Design of work position in manufacturing industry based on Rapid Entire Body Assessment (REBA) tool. *International Journal of Applied Engineering Research, 9*(22), 12565–12576.

Slatter, R. R., Husband, T. M., Besant, C. B., & Ristic, M. R. (1989). A human-centred approach to the design of advanced manufacturing systems. *CIRP Annals-Manufacturing Technology, 38*(1), 461–464.

Söffker, D., Flesch, G., Fu, X., Hasselberg, A., & Langer, M. (2011). Assistance and supervisory control of operators in complex human-process-interaction. In Applied electrical engineering and computing technologies (AEECT), 2011 IEEE Jordan conference on (pp. 1–6).

Suksawat, B., Hiroyuki, H., & Tohru, I. (2007). A model of communications for anthropocentric cell manufacturing system. In Control, automation and systems, 2007. IC-CAS'07, international conference on (pp. 1514–1517).

Tan, J. T. C., & Arai, T. (2010). Analytic evaluation of human-robot system for collaboration in cellular manufacturing system. *Advanced intelligent mechatronics (AIM), 2010 IEEE/ASME international conference on* (pp. 515–520). .

Thomas, C., Stankiewicz, L., Grötsch, A., Wischniewski, S., Deuse, J., & Kuhlenkötter, B. (2016). Intuitive work assistance by reciprocal human-robot interaction in the subject area of direct human-robot collaboration. *Procedia CIRP, 44*, 275–280.

Tortorella, G. L., & Fogliatto, F. S. (2013). Method for assessing human resources management practices and organisational learning factors in a company under lean manufacturing implementation. *International Journal of Production Research, 52*(15), 4623–4645.

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management, 14*(3), 207–222.

Treville, S.de., & Antonakis, J. (2006). Could lean production job design be intrinsically motivating? Contextual, configurational and levels-of-analysis issues. *Journal of Operations Management, 24*(2), 99–123.

Trist, E. L., & Bamforth, K. W. (1951). Technological content of the work system defences of a work group in relation to the social structure and of coal-getting: An examination of the psychological situation and some social and psychological consequences of the Longwall method. *Human Relation, 4*(3), 3–38.

Tzafestas, S. (2006). Concerning human-automation symbiosis in the society and the nature. *International Journal of Factory Automation, Robotics and Soft Computing, 1*(3), 6–24.

Uden, L. (1995). Design and evaluation of human centred CIM systems. *Computer Integrated Manufacturing Systems, 8*(2), 83–92.

Vathoopan, M., Brandenbourder, B., & Zoitl, A. (2016). A human in the loop corrective maintenance methodology using cross domain engineering data of mechatronic systems. In Emerging technologies and factory automation (ETFA), 2016 IEEE 21st international conference on (pp. 1–4).

Weiss, A., Buchner, R., Tscheligi, M., & Fischer, H. (2011). Exploring human-robot cooperation possibilities for semiconductor manufacturing. *Collaboration technologies and systems (CTS), 2011 international conference on* (pp. 173–177). .

Wittenberg, C. (2002). Bridging the gap between the human operator and the far away technical system by means of pictorial computer graphics and mobile devices. *IFAC Proceedings, 35*(1), 351–356.

Wittenberg, C. (2016). Human-CPS Interaction-requirements and human-machine interaction methods for the Industry 4.0. *IFAC-PapersOnLine, 49*(19), 420–425.

Womack, J., Jones, D. T., & Roos, D. (1990). *The machine that changed the world: The triumph of lean production.* New York, NY: Macmillan.

Wu, B., & Seddon, J. J. (1994). An anthropocentric approach to knowledge-based preventive maintenance. *Journal of Intelligent Manufacturing, 5*(6), 389–397.

Yang, X., Deines, E., Lauer, C., & Aurich, J. C. (2011). A human-centered virtual factory. *Management science and industrial engineering (MSIE), international conference on* (pp. 1138–1142). .

Yang, S. M., & Lee, S. Y. (1996). An approach to a human-centered CIM based on production information systems. *International Journal of Human Factors in Manufacturing, 6*(4), 349–363.

Zhang, X., Schmidt, L., Schlick, C. M., Reuth, R., & Luczak, H. (2008). A human task-oriented simulation study in autonomous production cells. *International Journal of Production Research, 46*(18), 5013–5041.