Cobots in Industry 4.0: A Roadmap for Future Practice Studies on Human–Robot Collaboration

Astrid Weiss, Ann-Kathrin Wortmeier, and Bettina Kubicek

Abstract—**With the vision of Industry 4.0 and cobots, working conditions in industrial settings are starting to change. We review related literature from the fields of human–robot interaction, work and organizational psychology, and sociology of work, as well as an exemplary project case study, and identify research gaps regarding the implications of cobots for work environments. We argue that we are in a transition phase from automation to actual collaboration with robots in manufacturing, and that this will open up a new problem space for investigations, in which a practice lens will be crucial. Based on this, we propose a research agenda for social practice and workplace studies to explore the sociotechnical environment of Industry 4.0 involving cobots at the individual, team, and organizational levels.**

Index Terms—**Human–robot teams, Industry 4.0, sociotechnical systems, workplace, human–robot interaction (HRI).**

I. INTRODUCTION

THE promise of Industry 4.0 is to enable the factory of the future, including new types of intelligent information systems and automation as well as more flexible collaborative robots called "cobots." As industry specialists have stated, full automation—that is, removing the human from manufacturing—is not considered viable [1]. The envisioned goal is rather a shoulder-to-shoulder cooperation between humans and different types of intelligent machinery [2]. Incorporating actual human–robot collaboration (HRC) into assembly lines, however, is more complicated than automating individual workflows [1]. To date, research in human–computer interaction and human–robot interaction (HRI) with regard to Industry 4.0, automation, and cobots has focused on operators' experiences of working with these systems. Especially, when it comes to cobots, studies have predominantly focused on dyadic HRC scenarios in attempts to identify and support the appropriate levels of collaboration and automation [1]. However, like Palanque *et al.* [3], with respect to automation, we consider it timely to ask bigger-picture questions about cobots in Industry 4.0, namely, how will robot-supported work change sociotechnical dynamics in Industry 4.0, and how can we enable satisfying working conditions in hybrid human–cobot teams?

Due to the dominance of human factors and engineering perspectives in Industry 4.0 [1], we run the risk of not considering modern social practice understandings of humans as meaning-making actors in a factory setting. Computer-supported cooperative work (CSCW) was the first research community in applied computer science to stress the importance of having an in-depth understanding of social practices when designing technology [4], [5]. This can be considered *"the key achievement of the research field"* [6]. While the idea of applying CSCW techniques to HRI is not new, thus far research has mainly focused on studying performance in human–robot teams in the context of urban search and rescue [7]. However, recent practice approaches in CSCW can arguably contribute for understanding trust in human–agent collaboration [8]. Social practice and workplace studies offer rigorous analysis of actual work practices developed within CSCW, originally derived from phenomenological sociology [9]. Practice-oriented work explores *"historical processes and performances, longer term actions which persist over time, and which must be studied along the full length of their temporal trajectory [...], situated in time and space"* [10]. The strength of social practice and workplace studies is their ability to provide rich and detailed descriptions of collaborative work between human and nonhuman entities. For example, in the healthcare sector, such studies have revealed the contextual nature of clinical knowledge and the challenges involved in digitizing it [11]. It is these types of insights we are lacking for Industry 4.0 as it pertains to cobots in order to challenge preexisting narratives and enable actual robot-supported work. We believe it is time to use a CSCW approach in Industry 4.0 settings and to conduct more practice studies on cobots as technological readiness levels increase and the usage of cobots becomes increasingly collaborative.

In this article, we argue for more practice studies on cobots in Industry 4.0. After giving some background on cobots and Industry 4.0, we question typical narratives about cobots (improved safety, simple programming, enabling higher level collaboration, etc.) in relation to our key research themes: safety and usability, programming and teaching, trust and acceptance, task dynamics, and qualification requirements. Subsequently, based on an example research project, we outline relevant research gaps that should be addressed with practice studies. We outline

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a roadmap that combines the identified key themes and gaps into a research question matrix, outlining how practice studies can enrich our knowledge of cobots in Industry 4.0 at the individual, team, and organizational levels. Specifically, practice studies can offer an understanding beyond typical dyadic HRC studies of how robot-supported collaborative work actually affects the sociotechnical environment of Industry 4.0.

II. BACKGROUND

Industry 4.0 denotes an approach to enabling the next generation of manufacturing [12], [13]. It advocates the increased use of sensors, information and communication technologies, and advanced automation throughout factory facilities, promising shorter development times, increased customization, greater flexibility, and improved resource efficiency [14]. Its basis is so-called cyber-physical systems (CPSs): networks composed of physical products and resources as well as their digital twins. This interconnectivity enables material entities to communicate with their environment and, thus, impact decision-making procedures in the production process [15].

Ongoing research has attempted to identify and solve challenges faced by engineers and designers when developing novel interface and interaction paradigms for the envisioned factory of the future. Currently, a number of research projects (e.g., Manuwork,[1] Symbiotic,[2] and MMAssist[3]) aim to explore the feasibility of flexible automation and robotization that can be added or removed in assembly lines, supporting workers through collaborative interaction paradigms. Industry 4.0 is considered both a paradigm and a digital transformation that changes industrial companies' organizational boundaries and operations [16] and subsequently affects the structure and performance of work in industrial systems [17].

A. Automation Versus Robots Versus Cobots

Automation can be described as the delegation of functions from a human to a machine. According to a widely accepted definition, it *"is a process that controls a function or task without human intervention"* [18]. Digital technologies considered part of Industry 4.0—among others, the Internet of Things, CPSs, cloud technology, and big data—are likely to push automation even further. However, these technologies also blur the lines between the physical world and virtual space [19].

In general, the purpose of robotic technology in the factory context is to facilitate a specific production task. What makes a robot a "robot" is constantly under discussion [20]. However, an appropriate definition for a factory context is *"a tool whose configuration of sensors, actuators, and integrated control system provides a significant level of flexible, independent, and autonomous action"* [21]. A central component is that a robot has, to some extent, a physical instantiation, making it necessary for the robot and the human to coordinate their activities in the here and now.

Unlike robots designed for automation and unsafe work, collaborative robots are designed to work, interact, and collaborate with humans. Cobots, which are currently in development for industrial applications, are a new generation of robots that are not bound to any type of fencing and thereby transcend the boundaries and workspace limitations of standard industrial robots and automation [14]. The main features that distinguish a cobot from a traditional factory robot include improved safety features for working in close proximity with the operator and simplified programming to allow for flexible application, enabling simple deployment and redeployment within a factory [22]. In this way, a single advanced robotic technology can be bought and implemented across various applications, augmenting human activities such as assembly, packaging, and organizing [23].

Shared human–robot activities often include machine tending, wherein an automated machine manufactures or assembles a workpiece that must be further handled or finished by a human, or pick-and-place tasks, where items are moved from one place to another (typically packaging finished items or loading and unloading a pallet of workpieces) [23].

B. Human–Robot Collaboration

Cooperation and collaboration are different types of interactions. Although the terms are often used interchangeably in HRI research, there are conceptual differences between them [1]. While cooperation and collaboration are both characterized by close interaction and a common goal, they differ in the extent to which the work activities performed by the human and the robot depend on each other. In cooperation, humans and robots work on different subtasks that lead to a common end result (e.g., pick-and-place robots in production). In collaboration, all tasks are carried out by the human and the robot together such that coordination is required. Thus, collaboration is a sequence of shared actions toward a shared goal. It requires that both collaborators are actively engaged in the task.

Michalos *et al.* [24] envision different kinds of collaboration for future factory settings and point out that, in all settings, robots and human coworkers will need to share a workspace and have physical contact. However, HRC encompasses more than just working at the same time in the same place. HRC in Industry 4.0 needs to be understood as a complex sociotechnical arrangement, in which agency can no longer be exclusively attributed to humans but is distributed among humans and nonhuman agents, such as machines, robots, sensors, programs, and similar devices. Following Latour [25], Suchman [26], and Rammert [27], we argue that working with cobots in an Industry 4.0 environment creates new constellations of shared control and distributed agency. Activities are shared in not only a physical but also a social space [28], and the embodied nature of collaborative robots has several implications for their social interactions with humans and other robots [20], which we just have started to systematically explore and understand.

III. HRC IN INDUSTRY 4.0: CENTRAL RESEARCH THEMES

There are a growing number of applications and studies of HRC in the factory context, of which several aim to illustrate

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[1] Online. [Available]: https://manuwork.eu

[2] Online. [Available]: https://symbiotic-project.eu

[3] Online. [Available]: https://www.mmassist.at

TABLE I
TAXONOMIC CLASSIFICATION OF KEY THEMES IN THE RESEARCH AREAS OF HRI, WORK AND ORGANIZATIONAL PSYCHOLOGY, AND SOCIOLOGY OF WORK

Main research areas	**Key themes**
A. Safety and Situation Awareness (human-robot interaction)	usability and performance [31], [32], [33], [34] speed and separation methods [35], [36], [37], [38]
B. Programming & Teaching Cobots (human-robot interaction)	end user programming and interface design for minimal training [29], [39], [40] intuitive interaction [41], [42], [43] future interaction paradigms that allow high flexibility [44], [45], [46]
C. Task Dynamics (work and organizational psychology)	task design [47], [48], [49] shared control and responsibility [50], [51], [75], [27], [52], [53]
D. Trust and Acceptance (work and organizational psychology)	factors facilitating trust and acceptance [54], [55], [57], [56], [58], [59] errors, reliability, and faulty behaviour affecting trust [60], [61], [62]
E. Skills, Training, and Workload (sociology of work)	polarization of skill requirements [63], [64], [65], [66] empowering and upskilling [67], [46], [68], [69] new workloads [33] [70], [71], [49], [72], [59] structural changes to the labor market [73], [74], [15]

the potential and promise of cobots, particularly as alternatives to traditional robots (see, e.g., [29]). In the following, we question typical cobots in Industry 4.0 narratives in relation to dominant research themes in various areas in HRI (A. Safety and Situation Awareness, B. Programming and Teaching Robots), work and organizational psychology (C. Task Dynamics: Allocation and Responsibility, D. Trust and Acceptance), and sociology of work (E. Skills, Training, and Workload). The assignment of themes to research areas was based on the authors' own expertise and disciplinary backgrounds. Of course, these research topics overlap and in reality cannot be clearly assigned to only one research area. Moreover, we present literature as a taxonomic classification that we do not imply is complete. The categorization primarily serves as a structured presentation of relevant papers to show typical narratives and problems in cobot research. An overview of relevant related work is given in Table I. In conjunction with the subsequent section presenting an example research project, this identifies research gaps that we argue need to be addressed by future social practice and workplace studies.

A. Safety and Situation Awareness

The main technical narrative surrounding cobots is that their improved safety features allow them to be safely operated in close proximity to human workers without fences or cages [30]. Typical research questions explored in this respect include how safe operations can be maintained and how to avoid putting the human operator in the shared workspace at risk. A large body of research on cobots addresses aspects of safety in relation to *usability and performance* aspects in assembly line production (see, e.g., [31]–[34]). Good usability should contribute to safe collaboration in shared workspaces. Another focus is exploring *speed and separation methods* (see, e.g., [35]–[38]), as defined in the available ISO standards for collaborative robots. Situational awareness and mode awareness are considered contributing factors to operator and process safety. We argue that future research on safety and situation awareness in human–cobot collaboration should not only focus on optimizing performance but also on whether the operator actually feels safe and whether situation awareness is given from an operator-centered perspective.

B. Programming and Teaching Cobots

Another common narrative is that cobots offer simplified programming, intuitive usage, and thereby flexible and adaptive application [22]. Typical research questions explore how programming environments need to be designed to enable low-skilled workers to have a greater role in programming and interacting with robots in the factory. A substantial body of research focuses on *end user programming and interface design* as well as educational technologies (see, e.g., [29], [39], and [40]). Another focus is exploring *intuitive interaction* (see, e.g., [41]–[43]). Simple programming environments (designed to be accessible to a variety of skill levels) should support operators with minimal training to provide input, programming, and reprogramming of the cobot. Several studies have shown that traditional teach pendants for programming and as input methods are not always the most intuitive or easy to use. Optimized input methods, however, are often only suitable for specific use cases. Therefore, ongoing research is exploring *future interaction paradigms that allow high flexibility for programming*, training, and using cobots that are still intuitive to use (see, e.g., [44]–[46]). We argue that future research should dive deeper into the topics of which interaction modalities for cobots are actually perceived as intuitive and how programming, teaching, and using cobots evolves over time for people with different skill levels.

C. Task Dynamics: Allocation and Responsibility

The ability to work around humans leads to the narrative that cobots can perform tedious, difficult, or dangerous operations in work cells occupied by humans but also that they enable higher level collaboration, including dynamic communication, optimization, learning, and program adjustments [29]. Typical research questions explored in relation to task dynamics include which tasks to allocate to the robot versus the human, what level of collaboration can be achieved, and how control and responsibility can be reasonably shared between the human and the cobot and can be made transparent. A great deal of research focuses on how work should be distributed between the human and the robot. Studies on *task design* (see, e.g., [47]–[49]) explore which tasks can be automated and how human abilities and competencies can be supported through sufficiently complex activities, which requires diverse cognitive operations such as planning, preparing, operating, and monitoring. Another stream of research focuses on *shared control and responsibility* (see, e.g., [27] and [50]–[53]). Studies have addressed aspects such as transparency, predictability, and the ability to influence a situation such that it evolves as intended by the controlling operator. Human–robot constellations are framed as hybrid networks that involve shared control between different human and nonhuman actors with complex control dynamics, where it can remain unclear who or what controls the situation. We argue that there is a need for more human-centered studies in this area that explore the conditions under which human operators still feel in control of and responsible for their actions and the overall work outcome.

D. *Trust and Acceptance*

Trust in robots has strengthened collaboration and interaction with and acceptance of robots [54], which led to the narrative that trustworthy designs are essential when it comes to operator acceptance of intelligent systems [55]. This is in line with related research on other forms of automation, such as decision support systems [56]. Typically, studies have addressed questions such as whether systems are designed such that they are trustworthy enough to be used appropriately and what level of trust is most suitable, with both too little (mistrust) and too much (overtrust) trust deemed problematic. Much ongoing research focuses on the *factors that facilitate trust and acceptance* (see, e.g., [54]–[59]). Factors influencing trust can be grouped into robot-related, human-related, and contextual factors, of which robot-related factors have received the most research attention thus far. Related research efforts have explored how *errors, reliability, and faulty robot behavior* affect human trust in robots, even though research reveals that high reliability does not necessarily lead to more trust (see, e.g., [60]–[62]). We argue that trustworthiness should not only be studied as a robot-related factor but needs to be understood as the default situation between the human and the cobot [62]. There is a need for more practice studies on how operators react to trust violations.

E. *Skills, Training, and Workload*

An implicit assumption is that "new" constellations of skills and learning strategies will be required in the context of Industry 4.0. The current debate in the social sciences is concerned with the ambivalent narratives of higher skill levels, risks of skill loss, and *polarization of skill requirements* (see, e.g., [63]–[66]). It is assumed on the one hand that there will be less need for highly skilled personnel in the future but, on the other, that employees will need to acquire new competencies or literacy to work with advanced technologies. A great deal of research focuses on *empowering and upskilling* the human workforce to foster problem-solving competence with on-the-job learning strategies and adequate competency management (see, e.g., [46] and [67]–[69]). Other research focuses on whether the introduction of cobots is associated with a reduced workload or rather creates *new workloads* (see, e.g., [33], [49], [59], and [70]–[72]). Empirical evidence indicates that, in Industry 4.0, manual and mental routine activities seem to be replaced, while analytical interactive work is becoming increasingly important. Current studies report moderate job losses due to these *structural changes in the labor market* and work organization (see, e.g., [15], [73], and [74]). We argue that these studies only show first indications of an increasing polarization of needed skills in specific sectors and the labor market in general, and that we need broader stakeholder involvement when studying the actual impact of cobots on the future of work in Industry 4.0.

IV. CURRENT RESEARCH GAPS

In the following, we briefly outline the project *AssistMe*[4] as an example case study to highlight and explain the shortcomings of the existing research on HRC in Industry 4.0.

The overall aim of the project [76] was to develop innovative interaction paradigms for a cobot in two different application contexts, namely, the assembly of automotive combustion engines [see Fig. 1(a)] and the machining (polishing) of casting molds [see Fig. 1(b)]. Three expansion stages of interaction paradigms were developed and subsequently evaluated together with operators in both application contexts. A standard Universal Robot UR10 system [see Fig. 1(c)] was used in the project with its teach pendant and the integrated programming and parameterization infrastructure.

The first application context—assembling a combustion engine at an automotive factory—included the installation of a cylinder head cover. The installation was carried out manually by stacking the cover onto the motor block with preinserted screws and teaching the cobot positions for automatic screw tightening. This collaboration was expected to provide assistance and reduce the workload at the workstation for the human worker, as the teaching only has to be performed once, and afterward, the shared collaboration is stacking the cover (human) and tightening the screws (cobot).

The second application context—polishing casting molds—consisted of positioning a workpiece and teaching the cobot, which eroded surfaces to polish. This collaboration was expected to substantially reduce the human workload. Manual polishing by air-pressure-driven oscillating polishing machines is extraordinarily labor intensive, nonergonomic, and harmful to health. The shared collaboration always included the teaching, as continuous casting molds are usually one-of-a-kind products manufactured in a lot size of one, with polishing by far the most labor-intensive production step, causing umpteen hours of labor per mold. Therefore, the teaching of positions is part of the shared collaboration.

The *AssistMe* project implicitly worked with several of the aforementioned narratives: the safety features of the UR10 allow safe operations, the simplified programming allows for intuitive usage and flexible application, higher level collaboration becomes possible, and workload is reduced. However, reflecting on the research conducted in the *AssistMe* project (and the aforementioned related work) revealed several research gaps with regard to these narratives that, in our view, can only be closed with future practice studies.

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[4] Online. [Available]: https://www.profactor.at/en/research/industrial-assistive-systems/roboticassistance/projects/assistme

A. Collaboration Partners

To date, the majority of HRI research has considered collaboration as a dyadic operator–robot relationship, and there is little research on larger team structures or the impact of the dyadic collaboration on other actors in the factory. In the *AssistMe* project, the focus was clearly on the one operator teaching and subsequently collaborating with the robot. It was not considered that the teacher and the collaborator could possibly be two different persons in the future. Moreover, other critically affected stakeholders—such as the union, maintainers, and shift leads—were hardly involved.

This dyadic usability-centric view limits the insights we gain regarding collaboration, as became evident in the *AssistMe* project. The developed interaction paradigms were not equally suitable for both application contexts. The collaboration worked well in the automotive context, but in the polishing use case, the robot did not perform the intended task accurately enough. This led to interesting insights with respect to the impact of collaboration: 1) operators were happy and proud that they could not be replaced by a robot; 2) as the robot did not perform the actual polishing task well enough, the overall collaboration was considered unsuitable, even though the developed interaction paradigms worked well; and 3) the industry partner lost trust that cobots were appropriate for them.

Moreover, we need to consider that even target users may not always wish for more intuitive interaction paradigms [41]. We need the bigger picture to understand why this is the case. At the moment, they are highly paid and skilled experts who are proud of their jobs. However, if anyone in the factory can easily program the cobots, everything changes, and there may be a risk of degradation of certain job profiles and skill sets.

These findings demonstrate that, in addition to focusing on human factors in dyadic collaboration, it is crucial for future studies to think about the different actors, roles, and work procedures affected in the manufacturing process in order to develop successful collaboration paradigms and thereby challenge the narratives of cobots as safe, flexible, and intuitive-to-use collaboration partners.

B. Collaboration Setting

In the automotive context of the *AssistMe* project, user studies were performed on the shop floor of the factory but not in the actual production line. In the polishing context, the studies were performed in the laboratory of the factory. While cobots have the potential to transform work in the context of Industry 4.0, little research has attempted to understand how cobots are actually being applied in manufacturing or to evaluate the actual implementation of cobots in the workplace. There are many examples of varying levels of HRC in research and industry (see [29] for a descriptive list), yet high levels of collaboration are only common in research studies but rather rare in actual industry applications. In industry, we rather see "stop/start" applications. In these constellations, cobots mainly work alongside human workers or perform repetitive or precise tasks. Clearly, these applications reduce strain and monotony for the human worker and take advantage of the cobot's ability to work in close human proximity. However, if the other features of cobots are not supported and tasks are simply split into human and robot tasks performed shoulder to shoulder, it becomes more likely that cobots will be used like traditional robots and replace rather than complement the human workforce.

Studying cobots in an Industry 4.0 setting poses the challenge that their actual implementation in the production line might negatively affect the factory's overall productivity. However, if we only study cobots in separate areas of a factory, we cannot gain insights into their overall impact on work. As one interview study in the *AssistMe* project demonstrated, having the robot in the actual line for only a short period of time revealed insights on not only the suitability of the interaction paradigm (too little adaptivity of the robot's work speed) but also the impact on the work atmosphere (operators no longer wanting to work in that cell because it negatively affected their social contact with coworkers) [77].

C. Collaboration Dynamics

Because most studies are conducted in controlled settings, we lack understanding of whether and to what extent cobots will change work over time. In the *AssistMe* project, we learned about the immediate impact of the robot on the work rhythm in the human–robot dyad and how this affected the social organization of work only because the robot was actually deployed in the production line for a longer period of time [77]. As empirical evidence shows, the experience of robots in factory settings changes over time, and qualitative methods can help reveal how robots affect the sociotechnical work environment over a longer period of time [78].

When it comes to trust in cobots, we identify a lack of studies on the creation, maintenance, and loss of trust over time in actual workplace settings. To date, most studies are conducted in laboratory environments and focus on short-term interactions. Moreover, research on the contextual factors influencing trust, such as type of task and organizational culture, is still in its infancy, strengthening our claim that workplace studies are needed in order to obtain a better understanding of how the sociotechnical context influences trust and reliance in HRC over time.

D. Control and Responsibility

There is a consensus that the limitations of automation and robotization lie in the requirement for humans to define system goals and to be responsible for their achievements as well as the negative consequences [79].

In the *AssistMe* project, the challenges of how to put people and robots in shared control through appropriate interaction design became apparent. Although the intuitive nature of the interaction increased in the three expansion stages of the interaction paradigms, the operator's scope of action and the cobot's functionality had to be restricted in order to achieve this. In other words, operators in the third expansion stage achieved the best performance on the specific task at hand but had no overall understanding of the system or means of fixing failures. The collaboration was totally driven by the cobot.

The issue of (un)controllability in sociotechnical systems leads to responsibility dilemmas culminating in an ethical debate about automatization and robotization of work. Comparative concepts of work that transfer control entirely to technology generally ignore the emergence of unintended consequences [50] and personal consternation in the case of negative events and, thus, the need for human intervention.

In the case of sharing control with cobots in uncertain and complex work constellations, concepts that enable humans to have control over technical systems and their work devices will be crucial [50], [71]. Even the best-designed interaction paradigm for a cobot cannot cover all possible incidents, as autonomous robot behavior will always include unpredictable consequences. However, we need to design means of making robot behavior more traceable and allowing humans to recover from failure situations that occur during collaboration. Moreover, studies from a sociopsychological perspective on the implications of shared control on robot-supported work remain scarce. The use of cobots and other networked technologies changes the roles and tasks of people in the work process, which can ultimately lead to reduced willingness to take responsibility. As we experienced in the third expansion stage of the *AssistMe* project, operators might experience themselves only as someone who keeps the system running throughout the entire process but who has little influence on the outcome of the work process. While autonomy and self-determined action require a certain degree of personal responsibility, the delegation of decisions and tasks to artificial intelligence and robotic systems limits not only people's agency but also their perceived control and responsibility over the work process [80].

E. Job Profiles and Work Design

Very little work can be found on the subjects of required skills and future job profiles, especially with regard to working with cobots. Some researchers have addressed the idea of the "operator 4.0" [46], [81]; however, the underlying fundamental question is how job profiles and work organization should be designed in the future. In the *AssistMe* project, we followed the narratives that the cobot should support, rather than replace, operators, and that the interaction should be designed as intuitively as possible so that little training is required. Larger scale impacts of the human–robot dyad, such as changes in hierarchies, decision-making processes, authority, and traditional control, were not considered and were only revealed by coincidence as side aspects in the interview study [77]. There is a need to develop more holistic sociotechnical ideas of how cobots affect work organization on the shop floor [82]: namely, what do employees need to know, interpret, and critically reflect upon in order to work successfully with cobots? Interviews in the *AssistMe* project further revealed that operators were satisfied that the robot could not polish the workpiece as accurately as a human, as this reassured them that the robot would not replace them in the near future. A sociotechnical understanding of work organization needs to involve complementary approaches in which the human replaced and ignored [50]. In the *AssistMe* project, we should have considered how to share the polishing task between the robot and the human instead of fully automating it. Grote [50] emphasizes that all organizational entities should be involved in workplace designs, and that both human and technical advantages must be integrated, proposing the conceptual framework KOMPASS [(K) Complementary Analysis and Design of Production Tasks in Sociotechnical System] (see [83]). A further aspect is including human involvement strategies—beyond task-based performance evaluations of human–cobot interaction–in order to identify requirements for interaction characteristics, use, and adoption of cobots [82]. Research focusing on sociotechnical workplace designs should consider a relational perspective, which means that required skills, competencies, and control strategies within a specific human–cobot configuration need to be investigated and evaluated in relation to the work situation [84]. Fig. 2 visualizes our identified gaps.

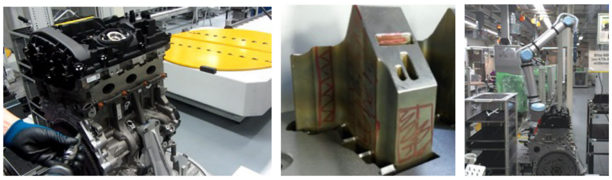

Fig. 1. Application contexts and robot used in the *AssistMe* project. (a) Combustion engine from the first application context. (b) Casting mold from the second application context. (c) UR10 cobot used in the *AssistMe* project.

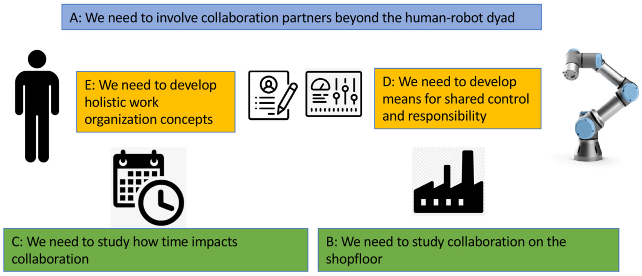

Fig. 2. Visualization of identified research gaps.

V. COBOTS THROUGH A PRACTICE LENS

In order to address the research gaps depicted in Fig. 2, we propose that more research be conducted through a CSCW social practice lens to understand how cobots are actually being applied in the manufacturing context. We need to explore how different human stakeholders experience this collaboration and how it affects the sociotechnical work environment. Such an understanding will inform, on the one hand, the design of improved future human–cobot interaction and, on the other, the creation of good working conditions in the future Industry 4.0.

In the following, we propose a roadmap for future studies on cobots in Industry 4.0. In order to address the need to involve all relevant stakeholders (research gap A), we suggest focusing on the 1) individual level, 2) team level, and 3) organizational level (see Table II) as units of examination. In order to cover the relevant research themes identified in Section III, we suggest targeting open research questions in the areas of 1) interaction

TABLE II
RESEARCH AGENDA FOR COBOTS IN INDUSTRY 4.0 FOCUSING ON SOCIAL PRACTICE AND WORKPLACE STUDIES

	Interaction Design	**Use and Adoption**	**Structural Impact**
Narrative	Enable safe, intuitive, and flexible interaction	Enable trustworthy, acceptable, and high-level collaboration	Less need for highly trained personnel and reduced workload
Individual	Focus: Role optimization RQ: How do we consider different roles in interaction design and programming interfaces? Studies: Workplace studies on task allocation	Focus: Technology adaptivity and trust RQ: How do we build trust in human-robot collaboration when system transparency and human control decrease? Studies: Social practice studies on situated trust	Focus: Shared control and competence RQ: What competencies and skills do operators need to work with and through cobots? Studies: Ethnographic long-term studies, qualitative interviews (to complement laboratory studies)
Team	Focus: Robot-supported work RQ: How can the interface design enable flexible deployment of cobots? Studies: Social practice studies on deploying the same cobot on different shop floors	Focus: Co-worker impact and team communication RQ: How can we promote team communication, shared mental models, and situation awareness in human-robot teams? Studies: Multimodal communication, use of psycho-physiological measures	Focus: Collaboration of multiple entities RQ: What are practical approaches to team collaborations under conditions of shared control and different qualification levels? Studies: Social practice and workplace studies
Organization	Focus: Novel collaboration scenario RQ: What could be creative collaborative applications of cobots beyond typical pick-and-place tasks? Studies: Living labs involving a variety of stakeholders	Focus: Organizational characteristics and management decisions RQ: What are the requirements of a socially acceptable implementation of cobots? Studies: Workplace studies with focus of employee participation	Focus: Changes in the educational system RQ: How does the education system respond to new digital qualification needs? Which actors are involved? What are the persistent forces? Studies: Stakeholder interviews (politics, educational landscape)

design (themes A and B), 2) use and adoption (themes C and D), and 3) structural impact (theme E). Research gaps B–E are covered by the types of research questions proposed.

To conduct a meaningful study on human–robot work in Industry 4.0, it is necessary to consider different human and nonhuman actors, both in dyadic and larger constellations. A cobot is never used in isolation from either other networked technologies or humans but is rather an integral part of how work is performed and perceived. In other words, human–robot work is, according to our understanding, not an isolated individual process between a synthetic average operator 4.0 [81] and the cobot but a collective process. With regard to the potential of cobots to change work in Industry 4.0 for the better, a view of only the human–robot dyad does not suffice; as such, we added the team and organizational levels as units of examination.

Ideally, our roadmap would be implemented in transdisciplinary projects that aim to answer research questions in all three areas, perhaps even for all three units of examination. However, answers from studies on single research questions would also serve as building blocks to better understand and design robot-supported work. We are aware of the complexity of the overall phenomenon that needs to be systematically studied and that the layers of interaction design, use and adoption, and structure are not a complete representation or concept. Rather, they are a metaphor standing in place of Industry 4.0 as a sociotechnical system. In sociological terms, our research agenda aims to achieve medium-range insights and is subsequently subject to constant technological and social change.

A. Interaction Design

To realize the promise of cobots as safe and intuitive collaborators that can be flexibly and adaptively used in the factory of the future, we promote a paradigm shift in interaction design toward robot-supported work and creative collaborative application scenarios. This requires practice-based research on interaction dynamics depending on different roles, workplace studies on programming and training interfaces, and exploratory research on collaboration scenarios for Industry 4.0 integrating cobots.

1) Individual Level—Role Optimization: Future studies on interaction design at the individual level should focus on the different roles of humans in contact with cobots. Operators, maintainers, programmers and teachers, and bystanders will all be differently affected by cobots in their work. Workplace studies will be needed to determine an optimized allocation of tasks among all these parties. Optimizing for these different roles should also consider that a person may need to switch among all of these roles during the workday and should account for this in the interaction design. Questions that fellow researchers might ask in this area include: How should multiple roles be handled? How should tasks be allocated among different human and nonhuman actors? How should different skill levels be handled? Robot-centered research can then build on these insights and focus on advanced human sensing capabilities, including monitoring human motion, detecting humans' intended motions and goals, and thereby increasing the fluency of HRC.

2) Team Level—Robot-Supported Work: At the team level, future interaction design research through a practice lens should start by reframing the perspective from *appropriate levels of automation* to *robot-supported work*. Here, it will be crucial to identify ways to increase the capacity of the cobot so that it can be quickly adjusted and reprogrammed to augment work. Within this reframing, the cobot should be considered a hybrid teammate, as opposed to just another automation technology. From the perspective of the human collaborator, not being involved in the workplace design can lead to detachment. Relevant research questions might include: What kind of training will be provided to the human worker to introduce them to these new kinds of robots? How can the necessary flexibility of the cobot interface be designed so that it can be deployed on demand at different production steps? This also needs to involve new perspectives on designing robot programming interfaces and the cobot's capabilities with respect to adapting to different team member capabilities and locations on the shop floor.

3) Organizational Level—Novel Collaboration Scenarios: As previous research has shown, categorizing tasks as either automatable or nonautomatable had a negative effect on the overall work experience. Instead, creative collaborative application solutions must be identified that facilitate flexible reprogrammable implementation for specific factory contexts. The *Volvo Group Collaborative Robot Systems Laboratory* offers an interesting approach to how universities, industry, and startups can work together to identify, prototype, and implement such solutions [85]. However, subsequent ethnographic research is needed to explore the depth and complexity of the collaboration between the human and the cobot.

B. Use and Adoption

In order to achieve a successful appropriation of cobots as trustworthy acceptable collaboration partners, we suggest focusing on human competencies, social norms, and the actual organization of work. We need a social practice understanding of how these factors impact the sociotechnical arrangement between human and nonhuman entities in the factory.

1) Individual Level—Technology Adaptivity and Trust: Research on adaptivity and trust should focus on how cobots and Industry 4.0 can be designed to better meet human competencies and needs [49]. Moreover, since use and adoption depend on whether operators trust the technology, an important future question is how to build trust in HRC when system transparency and human control decrease [60].

2) Team Level—Coworker Impact and Team Communication: At the team level, future studies need to consider that use and adoption is influenced by social norms and coworkers' attitudes toward a given technology. It can be expected that more flexible forms of work organization, such as semiautonomous working groups, will increase in factories due to the development of cobots. Future research should, therefore, investigate how team communication, as well as shared mental models and situation awareness, can be promoted in human–robot teams. A promising research approach seems to be multimodal communication approaches and the use of psychophysiological measures as input for robots to infer operator states, such as cognitive load or negative affect [86]. These inputs can then be used by the robot to alter its behavior.

3) Organizational Level—Organizational Characteristics and Management Decisions: At the organizational level, future research needs to acknowledge that the use and adoption of cobots depends on how they are implemented in factories and integrated into work processes [87]. For example, the same cobot could have different effects on use and adoption depending, for example, on whether a human-centered approach is taken to the development and deployment of the technology or organizational strategy and design. Organizations can, therefore, actively decide to improve the use and adoption of cobots and their impact on work design and thus important outcomes [49]. As we know from studies on organizational change [88], applying a participatory approach could help consider actual work practices as well as workers' competencies and needs early in the process and promote the use and adoption of cobots and their positive effects on work design and quality.

C. Structural Impact

To explore whether cobots actually increase the need for more highly skilled workers and will not cause job losses, we suggest transdisciplinary research at the intersection of technology development and labor science. We need to rethink the coshaping of learning technologies and learning humans in order to create satisfying working conditions for humans and productivity-enhancing cobots.

1) Individual Level—Competence and Control: In collaboration with cobots, it will be crucial to identify the qualification requirements under conditions of distributed agency and shared control. What competencies and skills need operators in an industrial context (e.g., prefabrication) in order to work with and through cobots? Furthermore, we need a sociotechnical understanding of shared control generated by empirical field studies, which currently does not exist. We need both qualitative interviews and laboratory experiments to outline the expectations of future qualification needs. In particular, with regard to skill loss, we need long-term iterative studies to observe changes in competencies and human reliance on cobots. In order to overcome the lack of field studies, upcoming research should engage in pilot projects or living labs, including participatory strategies.

2) Team Level—Collaboration Among a Multitude of Entities: The smart factory will also require collaboration among a multitude of entities within a team. Even if existing narratives promise that collaboration processes will be made easier through digital devices, research in the field of science and technology studies has shown that these expectations have not been fully met, and that practical approaches are needed for collaboration on the project level as well as for interorganizational learning [89]. In the context of cobots, we should consider interpersonal teamwork resulting from shifts in training and qualification. For example, increased polarization in the labor market will also impact team dynamics. Apart from the assumption that polarization of the labor market is not socially desirable, ethnographic methods, in which the researcher becomes a member of the research unit, are suitable here for outlining team dynamics under conditions of very different qualification levels.

3) Organizational Level—Changes in the Educational System: An identification of new competencies and skills and/or their rearrangement will require on-the-job training strategies as well as shifts in current educational systems, especially the German vocational system. How does the education system respond to new digital qualification needs? Which (human and nonhuman) actors are involved? What persistent forces can be observed? For this purpose, qualitative interviews with stakeholders in the educational landscape should be conducted. In addition, researchers should use participatory observations to capture the decision-making process.

VI. CONCLUSION

In an Industry 4.0 context, human labor can easily seem unattractive in comparison with cobots and other networked technologies. The narrative of cobots enabling safe, intuitive, and flexible interactions—as well as trustworthy, acceptable high-level collaboration without the need for highly trained personnel—sounds very promising, especially for small and medium-sized enterprises (SMEs), where employee turnover and production fluctuations are difficult to tolerate. However, as our article shows, automation in the form of cobots has currently only found its way into the world of work in limited applications. As yet, it has not replaced entire job profiles by far, but instead has involved easy-to-automate aspects of collaborative tasks.

In future research on cobots, we need a shift in perspective toward enabling robot-supported work rather than optimizing dyadic operator-robot constellations (see [90]). We should aim to see humans and cobots less as a dichotomy but rather as human and nonhuman actors in a sociotechnical network that needs to be designed as such. There is a need to explore in more detail which subaspects of workflows can be usefully automated; how much depth and complexity collaboration can and should achieve; and how this will ultimately affect people's (cognitive) workloads, required skills and training, and perceptions of the quality of work performed by humans. We also need to consider that the use of cobots and other networked systems in the Industry 4.0 context may lead to a diffusion of responsibility. The attribution of agency and associated role expectations to cobots reduces human agency through changes in the role structure in the sociotechnical system. Self-dependent action by humans, as well as the assumption of responsibility and control over the process and the result, becomes more difficult and less likely.

One might argue that it is somehow inferable that cobots are not yet as salutary to SMEs and Industry 4.0 as envisioned in the typical narratives, as the world is full of technical systems that are not adopted such that their more complex features are sustainably used right away. This is an enduring theme in CSCW and HCI research. However, as the first projects (such as AssistMe) encounter these effects with regard to cobots, it is relevant and timely to study the particulars of sociotechnical networks involving cobots. In this article, we have outlined which insights on cobots and Industry 4.0 are lacking so far and provided a roadmap for social practice and workplace studies that we are convinced can close these gaps. Despite the dominance of engineering-based robot narratives and a preference for laboratory-based studies on HRC, initial field studies on cobots indicate that people evaluate and categorize robots based on how well they fit within their everyday work routines [91]. To develop appropriate robot designs for robot-supported work, we need to get input from various scientific disciplines, including robotics, design, psychology, sociology, and so on (a broad consensus in the HCI and HRI research community), but also from affected stakeholders (operators, maintainers, shift leads, etc.), who need a stronger voice in the development process. An increased focus on social practice studies can offer this and will help build accounts of adoption and use across many different cobot applications and better understand how this technology can actually improve working conditions for people, rather than "just" improving the interaction paradigms of robots.

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