Of Embodied Action and Sensors: Knowledge and Expertise Sharing in Industrial Set-up

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ABSTRACT: Knowledge and expertise sharing has long been an important theme in CSCW and, importantly, one that has frequently challenged a prevailing view concerning knowledge management. This critique focused, initially, on the practical problems associated with issues of Organisational Memory (OM), and in particular the difficulties inherent in an oversimplified 'repository' model. Attention then turned to issues of contextuality and communication for expertise sharing, drawing on concepts such as communities of practice and social capital to understand, again, the sharing of knowledge and expertise in practice. Here, we report on how particular kinds of 'embodied action' can be identified in relation to the potential of cyber-physical infrastructures for knowledge sharing in an industrial context. We argue that, in a complex industrial domain, both the recording of physical movement – 'showing' – and the representation of local knowledge – 'telling' – are potentially relevant. Our proposal is that the evolution of cyber-physical infrastructures now offers a way of changing some early assumptions about how knowledge might be captured and displayed. We argue that we are entering a third generation of knowledge and expertise sharing research, where the use of augmented reality (AR) and sensor technology will result in significant new methodological innovations, including the capture and sharing of knowledge, embedded in embodied action.

Keywords: augmented reality, cyber-physical systems, didactic practices, know how, know that, knowledge and expertise sharing, local knowledge, organisational memory, tacit knowledge, sensor technology

1 INTRODUCTION

Since its inception, a classic problem in CSCW has been how to capture, describe and demonstrate real-world knowledge and skills so that this can be drawn upon by other people. The concern is shared with some other domains as well, notably the field of Knowledge Management (KM), where the focus has been on practices associated with managing knowledge work. This includes not just the service sector, with highly skilled professionals working with intangible goods, but also manufacturing, especially advanced manufacturing and the production of complex products, where blue-collar workers are often actively engaged in planning and coordination (Schmidt, 2012; Nonaka and Takeuchi, 1995).

Attempts to understand how knowledge and expertise can be shared have generated an abiding interest in the ontological and epistemological dimensions of knowledge. It was Ryle (1945, 2009) who famously distinguished between ‘knowing how’ and ‘knowing that’. The point of this distinction was to show that:

> “When a person knows how to do things of a certain sort (e.g., make good jokes, conduct battles or behave at funerals) his knowledge is actualised or exercised in what he does. It is not exercised … in the propounding of propositions” (op. cit., p.8).

‘Knowing that’, by contrast, is perfectly open to propositional expression; for instance, knowing that it takes 2 hours and 15 minutes to travel by train from London to Paris can be represented in a timetable. ‘Knowing how’, on the other hand, requires no theoretical understanding but simply describes how the body acquires certain learned habits. This distinction has occasioned considerable debate (Ackerman et al., 2013; Schmidt, 2012), not least in the KM literature (Hager, 2000; Tuomi, 1999; Howells, 1996; Spender, 1996).

Our intention in this paper is not to extend these debates. However, it is worth noting that, following on from Polanyi (1967), the notion of ‘tacit knowledge’ became fashionable in a number of quarters. In their discussion of a ‘knowledge-creating company’, Nonaka and Takeuchi (1995) attempted to operationalise this concept for KM purposes. Since then it has come to dominate in much of the KM literature. However, such attempts, at least sometimes, appear to mystify the idea of judgement or indeed, practice, through what, in our view (and others – see Schmidt, 2012) are spurious appeals to the ‘tacit’. The point would be that, if one accepts that certain kinds of knowledge have this mysterious quality, then methodologies for making it explicit and formalisable are needed.

We (as many others) have some serious reservations about this view. Our own studies indicate that much so-called ‘tacit’ knowledge is not tacit at all and is regularly articulated in conversation or manifested in gesture, glance, gaze and so on. It is, however, done in highly contingent and local circumstances (see e.g. Randall et al., 1996). The fact that ‘know how’ has no propositional content does not mean it cannot be described, understood or learned, or that such descriptions will not sometimes need translation into propositional statements. However, such descriptions will, as and when they are deployed, be contingent and to a purpose. Further, and as we shall see, there is no particular reason to assume that non-propositional knowledge *has to be* translated into a propositional form. This, of course, raises a further issue, which has to do with the 'local' character of some knowledge. As has been pointed out on a number of occasions, not least by parties to this paper, much work *practice* remains 'invisible'. 'Know how' may well be important to participants to a work activity, but its importance may not be recognised by others. In contrast to the conventional KM view – that the key issue is how to formalise the tacit through documentation and other constructs or, through more mundane methods – we identify just how (typically) non-propositional knowledge and, moreover, knowledge which has a 'local' character, may be deployed with a view to understanding how it may be displayed using more innovative technologies. More to the point, however, the various kinds of possible support will need to be configured so as to reflect the different kinds of knowledge and expertise being displayed and the different modes in and through which they are displayed.

Hager (2000) has made the point that investigating 'know how' carries with it certain assumptions about the need for qualitative approaches. Our own work, alongside that of many others in CSCW and HCI (see e.g. Clarke et al., 2003; Harper et al., 2000; Luff et al., 2000; Bowers et al., 1994) testifies to the fact that local, 'tacit' and otherwise 'invisible' work *practices*[1] can be rendered visible (largely unproblematically) through careful observation.

[1] This is not to conflate 'invisible work' with 'tacit knowledge', though it has been argued in the literature that tacit and contextual knowledge is one of the 'many guises' that invisible work can take (Nardi and Engeström, 1999, p.2). To clarify, invisible work has been discussed in the literature as: work that happens behind the scenes; routine or manual work entailing unacknowledged problem solving; work undertaken by people who remain unaccounted for; or informal work that is outside any job description, yet vital for collective tasks and company organization (Nardi and Engeström, 1999). In turn, 'tacit knowledge' has been mooted to be: 'non-codified knowledge' acquired through learning-by-doing (Roberts, 2000); 'highly personal' and 'difficult to formalize' (Nonaka, 1991, p.98); 'deeply rooted in action' and 'context' (Matthew and Sternberg, 2009; Nonaka, 1991), 'not yet … abstracted from practice' and 'applied in the state of the flow' (Spender, 1996, p.67). In Agyris' (1999) view, constant use of a particular instance of knowledge leads to internalisation and its automatic use. It thus becomes understood or implied without being articulated, and as such, is usually taken for granted and goes unnoticed (Baumard, 1999).

Nonaka himself (1991) notes how 'tacit' knowledge concerning bread kneading can be grasped by an apprentice through close observation of the work practices of an expert bread maker.

Nevertheless, there is also agreement that it is by no means trivial for workers to capture for themselves these kinds of practices or the non-propositional knowledge that might be embedded in them. A key issue here is *time*. Workers are typically under pressure to achieve a range of goals that do not allow much time for reflection. This being the case, the overhead created by knowledge and expertise sharing activities can appear, at least at first, to be overwhelming (Ackerman and Malone, 1990; Schmidt, 2012). A second issue relates to privacy and trust and the desire to retain one's competitive edge and status within a company. Thus, some workers are resistant to the idea of sharing their knowledge – especially knowledge acquired through hands-on experience over many years (Brown and Duguid, 1998; Nonaka, 1994). Beyond this, there is also an issue of having what Schmidt describes as the 'expositional and didactic competencies required to formulate their experiences so that it is understandable for a remote and possibly unknown readership' (Schmidt, 2012, p. 206). In other words, it is hard to express 'know how' in a generic form such that just anyone might be able to make sense of it.

Despite our apparently critical stance, we acknowledge the advances that have taken place in knowledge and expertise sharing over the past few decades. Ackerman and his colleagues, for instance, successfully addressed a number of key issues for knowledge and expertise sharing through their implementation of Answer Garden (AG) 1 and 2, which built upon tools that had already been designed to support certain aspects of organisational memory (Ackerman and Malone, 1990; Ackerman and McDonald, 1996). Other tools have followed in the wake of these early endeavours (see Ackerman et al, 2013, for a review of the more important developments). However, the key issues outlined above, we suggest, may be open to solutions that the CSCW community has not yet fully explored.

On occasion, new technologies bring with them significant new affordances. Recent advances in the capacity of AR-based cyber-physical systems (CPS), put together with the potential opportunities offered by the Internet of Things, are about to provide just this kind of a technological step-change. This, we suggest, will bring with it new ways in which knowledge and expertise might be captured and shared. Put another way, AR provides insights into how the cyber-physical innovation might afford the sharing of knowledge and expertise. This relates especially to local and embodied knowledge, which, setting aside the various debates, is generally acknowledged to be difficult to capture and share (Ackerman et al., 2013; Fitzpatrick, 2003).

If we accept the above arguments, it follows, pace Nonaka and Takeuchi, 'know how' does not necessarily need to be transformed into propositional content for effective knowledge sharing to take place. A range of other possibilities might be considered. Amongst these is the ostensive provision of information about 'know how' by using video, virtual reality and – increasingly, as the relevant technologies mature - AR and sensor technology.

In this paper, we elaborate on some initial ideas about the use of CPS and AR technology that have already been discussed in CSCW (Ludwig et al., 2017; Robertson and Wagner, 2015), with the specific goal of advancing the state of the art concerning knowledge and expertise sharing. We do so by reporting on ethnographic data collected in an industrial context (itself under-reported in the CSCW and HCI literature), with the aim of identifying some of the embodied 'know how' that could fruitfully be shared for one specific activity: set-up for bending machines[2]. This has been selected because of its perspicuous character for investigating the potential role of sensor technology in the representation of workplace practices, as will be later clarified. To the best of our knowledge, articulation of the use of CPS for knowledge sharing in industrial set-up has not been addressed in the CSCW or HCI literature. These three factors, together with our discussion of how this instantiates a possible new approach to knowledge and expertise sharing, are the key contributions of this paper.

The paper is structured as follows: First of all, we examine related work, looking in particular at how knowledge sharing has been discussed in various domains. After this we present our research in more detail and our methodological approach. We then look at the empirical results, focusing on the relevance of knowledge to industrial set-up processes, and the difficulties entailed in sharing it. After this we introduce some design implications that need to be born mind when seeking to support knowledge and expertise sharing in these kinds of industrial contexts. This is followed by a discussion of the findings and design implications, elaborating how CPS-related AR and sensor-based technologies might fuel a step-change in knowledge and expertise sharing support. Finally, we conclude by pointing to new directions that might fruitfully be pursued in knowledge and expertise sharing research.

2 RELATED WORK

Aiming at setting the background for the later discussions in the paper, we start this section by revisiting some of the key texts concerning the knowledge-intensive character of industrial set-up. We then look at the CSCW literature on knowledge and expertise sharing, which forms the central backdrop to our arguments. We follow by examining literature on embodied action, particularly focusing on the methodological aspects of the bodily and spatial aspects of human

[2] For an overview of what set-up for bending machines entails, see section 4.1.

action that, in our view, make the debate on its relevance to knowledge and expertise sharing interesting. The section on AR technologies discuss how this type of technology can support the recording and visualisation of knowledge embedded in embodied action. We conclude by looking at some of the literature that shows the potential of CPS for knowledge and expertise sharing. We show that, despite the potential identified in the literature, little has been said about how it actually responds to user needs and requirements. This highlights the relevance of the research study herein presented and outlines the research gap that it sets out to address.

2.1 Knowledge and expertise sharing in industrial contexts

Most of the discussion regarding knowledge and expertise sharing in manufacturing and industrial contexts is located in the KM literature. In view of its scale we cannot provide a comprehensive account of that literature here. However, certain parts of it are pertinent to both our own position and arguments previously made in CSCW, so we will briefly examine those elements as background to everything else that follows.

Studies of knowledge and expertise sharing in KM widely acknowledge the importance of knowledge management as a strategic resource for companies, offering potential competitive advantages in the marketplace (Watson and Hewett, 2006; Grant and Baden-Fuller, 2004; Argote and Ingram, 2000; Grant, 1996; Spender, 1996). However, none of these studies explicitly examine the role of expertise sharing and knowledge transfer in industrial set-up processes. Instead, the focus is recurrently on elaborating models that might assist in understanding key elements of knowledge sharing among workers (Hau et al., 2013; Nonaka and Toyama, 2003; Nonaka et al., 2000; Spender, 1996; Nonaka, 1994). This has chiefly resulted in material covering either the essential elements of organisational knowledge creation (Nonaka and Toyama, 2003; Nonaka et al., 2000; Nonaka, 1994) or the motivational aspects that might encourage realisation of successful knowledge transfer, such as generation of social capital (Hau et al., 2013; Spender, 1996), which refers to the "the sum of the actual and potential resources embedded within, available through, and derived from the network of relationships possessed by an individual or social unit" (Nahapiet and Ghoshal, 1998, p. 243). Very little of this literature actually deals with knowledge intensive *practices* and how they might best be shared.

Practices need to be seen as 'ways of doing'; often predicated on knowing just how something is to be done, what organizational and other expectations attend on it, and how it can be recognised for what it is (Schmidt, 2014). Such matters are typically glossed as 'contextuality' but our task here is not to rehearse the point *that* knowledge is contextual but to show *how*, in this case, it is. This is particularly important where skills are manifestly 'embodied', relying on a 'feel' for things (see e.g. Clarke et al., 2003).

2.2 Knowledge and expertise sharing in the CSCW literature

Over the past few decades 'expertise sharing' has become a well-established field within the CSCW literature. Ackerman in particular has focused on this topic, bringing practices and the social setting to the centre of the CSCW discourse about how knowledge and expertise might be shared. Ackerman's work advocates acquiring a detailed empirically-based understanding of the practices associated with knowledge transfer, something that had hitherto been neglected in the literature (Ackerman and Halverson, 2004).

Amongst other things Ackerman's work has touched upon the notion of Organisational Memory (OM). This concept focuses on the storage of organisational knowledge in artefacts such as relational databases (Randall et al, 1996; Ackerman, 1998). For Ackerman, an essential step in OM is documenting an organization's structure to capture features that might be relevant to its 'memory' (Ackerman and Malone, 1990). Related literature discusses possible obstacles to the storage and use of OM. First of all, accessing memory can be troublesome (Randall et al., 1996) and many problems can arise, especially in distributed organizations or where a significant number of people are involved (Ackerman and McDonald, 1996).

However, OM involves more than just data storage. Over time, different systems and interests have evolved, but there has never been final agreement on the exact nature of the support such systems should provide (Bannon and Kuutti, 1996). At a deeper level, the metaphor of 'memory' has also been brought into question. Randall et al. (1996), for instance, argue that the:

> 'organisational memory' metaphor fails to distinguish the kinds of socially situated 'remembering' that might take place in organisational life, and provides few examples of the 'remembering how', remembering who', and 'remembering that' we are interested in (Randall et al., 1996, p. 29).

This critique resonates strongly with discussions of the grammatical order of concepts such as 'knowing how' and 'knowing what' outlined above. Thus, we return again to the problematic notions of tacit knowledge and propositional content.

It is worth noting here that, within the knowledge and expertise sharing paradigm, a distinction has been made between two research traditions regarding how knowledge and expertise flows among knowledgeable actors: 'knowledge sharing'; and 'expertise sharing'. These two ideas share many features and overlap in numerous ways but are differentiated by the status of the externalisation of knowledge. While externalisation plays an important role in knowledge sharing, expertise sharing is taken to be less dependent on prior externalisation (Ackerman et al., 2013; Pipek et al., 2012). This resonates with a view that expertise largely corresponds to embodied knowledge (Fitzpatrick, 2003). None of this, however, quite puts to bed the controversy surrounding 'tacit' and 'explicit' knowledge (Nonaka et al., 2000; Polanyi, 1967).

A core criticism here relates to how the concept of tacit knowledge confuses something that was originally a clear practice-oriented consideration. Schmidt (2012) puts forward a very strong argument against the dichotomy between tacit and explicit knowledge, expressing the view that the notion of tacit knowledge is 'a conceptual muddle that mystifies the very concept of practical knowledge' (p. 163). He, as ourselves, favours a focus on practices concerning the actual application of knowledge and their concomitant outcomes. For him, the important issue is to find out who uses which tools and to what level of detail. He also suggests a need for a deeper understanding of 'didactic practices' or 'mutual learning'.

Another way in which the sharing of knowledge and expertise has been differentiated in CSCW research refers to rhetorical focus. According to Ackerman et al. (2013), the first generation of knowledge and expertise sharing research concentrated on the technical characteristics of knowledge management. Thus, the creation of databases containing instructions and standard procedures were considered to be of central importance. However, the neglect of the lack of incentive structures (Tausczik and Pennebaker, 2012; Hsieh et al., 2011; Orlikowski, 1993) and of the social-technical gap created new issues instead.

Following the identification of this social-technical gap, CSCW research invested in illuminating the organisational and social realities of knowledge and expertise sharing. This was deemed to be imperative for the success of KM initiatives (Ackerman and Halverson, 2004), especially local and personal knowledge, which, it was argued, is difficult to capture (Ackerman et al., 2003). This led to a focus on notions such as communities of practice (CoP) (Ackerman et al., 2013; Wenger, 1998) and social capital (Nahapiet and Ghoshal, 1998), with CoP offering insights regarding the inherent relationship between shared practices and learning opportunities, and social capital assisting with the understanding of the conditions that could foster knowledge and expertise sharing.

Elaboration and discussion of these concepts represented a significant advance in our understanding of knowledge and expertise sharing. However, many questions remain unresolved. Our findings suggest that the missing piece is a focus on the possibility of transmitting non-propositional knowledge through observations of embodied action. To date, no research in CSCW has been addressed to this.

2.3 Embodied action and knowledge transfer

The notion of ‘embodiment’ has a long, and sometimes controversial, history. Research on embodied action has been, inter alia, influenced by Merleau-Ponty’s philosophy of embodiment (Gallagher, 2010; Crossley, 1995) and by Wittgensteinian philosophy (Wittgenstein, 1953). For ethnomethodologists and others, however, ‘embodied action’ is a visible and accountable matter, one where the purposes and rationales that actors bring to their activities can be identified in and through what is said and done (Lynch, 1997). As such, it becomes an empirical matter. In keeping with this perspective, then, we should emphasise here that *the fact that* knowledge and action are interrelated, and *the fact that* action is inevitably embodied, is not the point. This has been made abundantly clear by Merleau-Ponty and, before him, Wittgenstein. Our focus is on *how, in this particular context of embodiment, knowledge in action is manifest*.

We take an interest here, then, in how embodied action ‘in practice’ can be represented so as to confer information about meaningful behaviour that embodies ‘good practice’ and that is therefore valuable to share with others. Although research in CSCW has long had an interest in the sequential organisation of ‘talk-in-action’, Benford et al. (1995) nonetheless noted that ‘embodiment often seems to be a neglected issue’ (p.242) in cooperative systems. However, some studies have examined the reciprocal influence of actions and interactions in the virtual and physical worlds (see e.g. Bowers et al., 1996; Heath et al., 1995; Heath and Luff, 1991).

Heath and Luff's (1991) study of video-mediated communication, in particular, identifies the subtle but crucial ways in which the elegant and efficient management of collaborative work is realised through gestures and other visual behaviours.

Others have focused specifically on how embodied action is manifest in the treatment of physical artefacts (Harrison and Minneman, 1995; Brown and Duguid, 1994), for instance: the expression of intention through the movement of physical objects (e.g. repositioning an object in a workspace); the production of physical representations (e.g. writing or drawing on paper); deictic emphasis (e.g. underlining on texts); and the actual use of physical objects (e.g. working with computers, seeing and feeling objects, reading, etc.). According to Kendon (1990), and largely in keeping with Heath and Luff's (op. cit.) insights, *embodied action can* also *be related to other bodies*. Significant aspects here include issuing and receiving 'signs' in the form of visual indicators such as co-positioning, specific postures, gestures and facial expressions, not to mention oral and/or acoustic indicators, e.g. speaking and other (external) sounds. If we take these insights on board, it is apparent that supporting these embodied actions will require considerably more than recording propositional content. As we shall see in sections 2.4 and 2.5, although video and similar materials provide some access to our understanding of the 'embodied', we believe that new technologies will afford a richer set of possibilities.

2.4 AR, embodied action and the potential for knowledge and expertise sharing

The beginnings of AR technologies date back to the early 1990s (Feiner et al., 1993; Caudell and Mizell, 1992). From their earliest developments, their potential for blending useful information with real world surroundings has already been visible. With the emergence of new technologies like tablets and smartphones, the popularisation of such applications became a real possibility.

Research here has explored two main input and output mechanisms: conventional keyboard/mouse and displays (Gauglitz et al., 2014a); and the use of touchscreen and head-mounted displays associated with voice commands (Fakourfar et al., 2016; Zheng et al., 2015; Gauglitz et al., 2014b). Findings point towards users preferring the later solution. More recent developments have explored the use of gestures as possible interaction mechanisms for AR-based systems (Pollalis et al., 2017), but these are very early developments that need further research.

In terms of applications, much of the focus of existing research has been on mobile AR-applications to support synchronous remote or co-located collaboration. These cases commonly anticipate the in situ creation of content and its distribution among the actors (Langlotz et al., 2012; Henrysson et al., 2005). In keeping with this trend, Gauglitz et al. (2012, 2014b, 2014a) examine the scope for telecollaboration mediated by AR technology. In their work, sophisticated tracking algorithms have been devised to help remote users to place location-based annotations without marker recognition in the field of view of a local user. On the basis of this, novice users were able to follow instructions from experts, who were remotely placed. Evaluation showed that the proposed technology could aid novice users in following complex instructions quickly and with almost no errors (Gauglitz et al., 2012). Further developments of this application enabled remote users to act independently of the field of view of the local users, whilst still placing location-related annotations. Further results indicated that the proposed solution was both easy to use and of significant help in fulfilling the tasks in the described context (Gauglitz et al., 2014b).

The use of AR in knowledge-intensive environments to support learning processes has also been explored to some extent. A promising feature is fast, unrestricted and context-specific access to information (Klopfer et al., 2005). This type of technology allows for the following affordances, which are likely to be of use in an industrial context as well: (1) exploration of teaching materials from different angles; (2) supporting teaching where no real-world first-hand experience is possible; (3) enhancing collaboration between students and instructors; (4) helping students to control their speed of learning and decide which pathway to choose (Yuen et al., 2011). Findings from the literature also suggest that AR technologies can enhance workers' skills and perception, promising potentially sustainable improvement in things like assembly operations (Ong et al., 2008; Pathomaree and Charoenseang, 2005).

Others areas of application include construction and maintenance work (Lee and Akin, 2011; Wang and Dunston, 2006); inspection work (Dunston and Shin, 2009; Chung et al., 1999); and welding (Park et al., 2007).

Unsurprisingly, embodied action has arisen as an issue in this area. For instance, Fakourfar et al. (2016) highlight the role of *deixis* in AR systems, i.e. the use of gestures in the course of interaction, noting that deixis facilitates collaboration by allowing for common reference, thus acknowledging the importance of the bodily and spatial aspects of human action. This gives particular substance to the relevance of embodied action to knowledge and expertise sharing. Fakourfar et al. stress that AR annotation systems need to accommodate deixis, even if this leads to further challenges. Irlitti et al. (2017) comment on how the combined shared space provided by many AR systems allows people to use the same non-verbal cues they use in face-to-face interaction. Tang et al. (2007) explore the role of embodiment in particular detail in the use of mixed presence groupware, i.e. groupware supporting interaction between groups where some people are co-located and others are remote. The authors note that, when such systems do not account for the embodied actions that occur during collaboration, it leads to a phenomenon known as *presence disparity*[3]. The authors therefore suggest the need to provide mechanisms for embodiment in mixed presence groupware that can offset presence disparity.

Despite Tang et al.'s work (2007) we have found no discussion in the literature regarding how embodied action captured through AR systems can be used for knowledge and expertise sharing. Furthermore, little attention has been paid to scenarios of asynchronous collaboration (Irlitti et al., 2017), which is core to our own research. We set ourselves to address this gap in the literature and to contribute towards reducing it.

2.5 CPS and the lack of applications for knowledge sharing

Current and past research has shown that new technologies, when designed with a view to the social-technical context in which they will be deployed, can potentially support and facilitate numerous different processes[4]. The rise of AR and sensor technologies provides for new opportunities relating to the haptic and thence to a more nuanced understanding of the sequencing of activities. When allied to procedures for examining 'rationale' this offers potential for a richer picture of how knowledge and expertise are constituted and thus shareable. Cyber-physical systems (CPS), as they have come to be termed, have appreciable promise.

CPS are systems of tightly coupled physical and cyber components that integrate software, hardware, sensors and actuators. The general definition of CPS implies that they can link and manage distributed systems consisting of physical and virtual entities (Lee et al., 2015). Interaction with such systems takes place via a human-machine interface, which can be

[3] *Presence disparity* occurs when remote collaborators are not sufficiently aware of those who are co-located. According to Tang et al. (2007) it happens because embodied action is key for the processes of: *feedback and feedthrough,* whereby people perceive themselves and one another; *consequential communication*, where people grasp information by observing the work of others; and *gestures,* which correspond to 'bodily movements and postures used for communicative purpose' (p.5).

[4] Note that we do not buy into technological determinism but acknowledge technology's assistive potential.

implemented through conventional PC interfaces, touch screens or even AR-based technologies, as seen in section 2.4.

The possible application of sensor technology as a central feature of CPS, is extensive. In an industrial context, for instance, it has the potential to enhance human sensory access by controlling areas that are inaccessible to humans (Chong et al., 2003), and to provide additional information (Gellersen, 2005) of assorted kinds. Hu et al. (2016) and Marseu et al. (2016) discuss three types of sensor/actor relationship: (1) sensor-to-sensor interaction, (2) sensor-to-actor interaction; (3) actor-to-actor interaction. We argue that it is sensible to think of a fourth relationship – i.e. actor-to-sensor interaction – in situations where actors manipulate the outcome of a sensor.

Chen and Tsai (2017) look at the use of sensors in manufacturing and representative cases applying RFID and auto ID. The exact nature of a deployment depends substantially on the dynamics of the physical process and the degree to which it can be automated. At one extreme there is a notion of lean infrastructure without external interfaces. Here, sensors communicate with each other using a knowledge base that contains artefact-based knowledge about the current state of the environment (Strohbach et al., 2004). This requires no human interface because the knowledge base consists exclusively of data and rules for its processing (op. cit.). At the other extreme there is the notion of a CPS being totally supervised by humans. Here a key concern is how data can provide the right information for the right purpose at the right time to the right person (Lee et al., 2013).

Examples of CPS applications can be found in numerous domains including power electronics, aerospace, defence, energy systems, healthcare, and transportation (Hu et al., 2016). A useful overview of their potential and associated challenges can be found in Park et al. (2012) and in Poovendran et al. (2012).

In an industrial context CPS have been termed CPPS (Cyber Physical Production Systems). CPPS have been proposed as an answer to the progressive mechanisation and networking of machines and sensors, resulting in a flood of data (big data) that can be put to a variety of ends. Under the generic term Industry 4.0[5], this is seen to represent opportunities for entire industries to position themselves competitively for the future (Kagermann et al., 2013). Amongst other things, these systems have been considered for: predictive maintenance, automatic detection and remote diagnostic systems (Chen and Tsai, 2017); the development and operational phases in production (Herterich et al., 2015); and the location of trends and the scope for optimisation (Shi et al., 2011). Other research relates to software development for smart factories (Otto et al., 2014) and CPPS-based modelling (Thramboulidis and Christoulakis, 2016).

In view of CPS's potential for recording the haptics and detailed variables involved in work processes, which can in turn be visualised through AR-based technologies, it is conceivable that such systems may afford a methodological revolution in the gathering and disposition of knowledge, *including the knowledge embedded in embodied action*. As Wolf (2009) has argued:

> In the past, we have brought our information to computers in the predigested form of keystrokes and mouse clicks. Cyber physical systems actively engage with the real world in real time and expend real energy. This requires anew understanding of computing as a physical act – a big change for computing (p. 89).

Engaging with the real world entails knowing a great deal more about how (cooperative) activities and computation might be interwoven. Schirner et al. have referred to this as 'Human

[5] Industry 4.0 (I4.0), is a movement that has resulted from the German federal government calling for a 'fourth industrial revolution', inspired by the use of CPSs in manufacturing contexts (Paelke and Röcker, 2015; Wan et al., 2015).

in the Loop Cyber Physical Systems' and such an endeavour, as they say, 'poses tremendous challenges' (2013, p.36). To begin with there are potential difficulties stemming from the blending of interaction between physical and virtual worlds, resulting in increased interactional and technical complexity. As these are quite novel systems, there is also a need to develop prototyping tools to support the ideation process and user-centred and participatory design (Paelke and Röcker, 2015; Monostori, 2014; Lee, 2008). The main issue, however, concerns the applicability of CPPS and Industry 4.0 concepts to small and medium-sized enterprises (SMEs) (Ludwig et al., 2016). Another noted issue – that goes to the heart of our interest here – is the difficulty of converting the knowledge of skilled workers into program code (Bracht et al., 2011). Further areas of tension concern quality requirements, employee qualification and human-machine cooperation (Ludwig et al., 2016).

The aforementioned challenges remain subject to further research. In addition to that, it is worth pointing out that CPS-focused research has so far been mainly technology-driven. Thus, there is an evident need for research employing real-world user-centred design approaches to properly understand the requirements present in the social-technical contexts where such applications will be deployed. Furthermore, to the best of our knowledge, no research has yet examined how such systems might support knowledge and expertise sharing by gathering the knowledge embedded in embodied action. This paper is therefore geared towards addressing these two issues.

3 METHODOLOGY

The findings presented here come from a research project investigating opportunities for the design of technologies to support industrial set-up, a core and time-critical process whose optimisation is directly associated with enhanced productivity and competitiveness (Cakmakci, 2009; Palanisamy and Siddiqui, 2013; Shingo, 1985). Our research has been conducted under the auspices of the Design Case Study (DCS) methodological framework (Wulf et al., 2011). This approach involves the deployment of ethnographic (and other) approaches to the long-term study of existing practices, socio-technical innovation, the design of new artefacts (where necessary), and study of their long-term appropriation. We report here on the results from the first phase of the DCS cycle, also known as the pre-study. At this stage, we are primarily involved in understanding how existing practices are accomplished and what the possible ramifications for the design of new technology might be.

Ethnographic research, on which much of our early work is predicated, primarily aims at 'making the invisible visible' (Goodwin, 1994) by describing the implicit, social and cultural organisation that characterizes participants' activity (Anderson-Levitt, 2006). Although there may be many versions of what it takes to do this, we draw here on a more or less 'interaction analytic' view, which stresses the sequential organization of activities and the reasoning processes undertaken by those performing them and others who seek to understand them. Through their collaborative work, in this view, actors often engage in activities that are closely linked to each other, without necessarily explicitly discussing their actions (Heath and Luff, 1991). Put simply, mutual understanding is arrived at without recourse to explicit instruction. In keeping with Peter Winch's position (see Winch, 1964, 1997), we see a relationship between the way we understand others and the way we understand ourselves. As he asserts, 'My understanding of 'what I do' ... manifests itself in two ways: in the character of my behaviour itself; and in what I may say about my behaviour.' (Winch, 1997, p.195). All of us, experienced operatives or ethnographers, may perfectly well understand how we do what we do, but how we describe it to others is a different, and highly contextual, matter.

In the field of 'Workplace Studies' there is a growing interest in various way of representing visible behaviour, conversations and other possible behaviours, for analysis e.g. the interactive organisation of activities in: offices and call centres (Moore et al., 2010; Murphy, 2004; Whalen et al., 2002; Whalen, 1995); operating rooms (Mondada, 2012; Koschmann et al., 2007; Svensson et al., 2007; Hindmarsh and Pilnick, 2002); medical consultations (Beach and LeBaron, 2002; Greatbatch et al., 1993); etc. Much of this work has entailed careful analysis of video material and, again, there is an extensive literature discussing how such material can be made tractable for analysis (Knoblauch et al., 2008; Heath et al., 2007; see e.g. Mondada, 2006). In our case, because we needed a very close-grained analysis of set-up, we used video recordings and eye-tracking technology.

Specifically, shadowing sessions (Czarniawska, 2007) were performed for the collection of in situ data regarding work practices and social interaction. Supplementary eye-tracking videos provided details of the practical steps during a set-up process[6]. This, together with the transcribed comments of the participants, meant that even complex process steps could be recorded and evaluated in their entirety. Accompanying in-depth interviews (Hermanowicz, 2002) were conducted to enable detailed examination of the practices of knowledge transfer. These were also audio recorded and transcribed. A total of 14 shadowing sessions with accompanying eye-tracking recordings were performed. With the help of fieldwork notes, the interactions were documented before, during and after the sessions. There were 24 interviews of between 45 and 120 minutes. The transcription process used the 'intelligent verbatim' method.

[6] We used an eye-tracking technology to record actual set-up sessions in the course of ordinary workdays of our participants. By capturing the exact gaze of participants, we were able to get a better understanding of the operations they carried out. Eye-tracker recordings gave us both a better view of the parts being exchanged and the actions involved in the exchange. We also got participants to use a Think Aloud protocol (Nielsen, 1993, pp. 195-198) during the session, so as to gather information about their reasoning as the set-up progressed. Analysis of this data gave us a deeper understanding of what industrial set-up entails and underpinned heat-map analysis of the tools and parts the participants were focusing on.

In total, 24 workers from 4 different SMEs between the ages of 20 and 60 participated. 7 belonged to Company A, 13 to Company B, 2 to Company C, and 2 to Company D. All companies were medium-sized and produced cold-forming[7] parts. The interviewees held various positions in the company, came from different educational backgrounds and had different job tenures (see Table 1). We wanted to cover a diversity of profiles to gather a more nuanced account of the investigated themes. This is common practice in studies focusing on the design of technologies for a wide spectrum of end-users (Sharp et al., 2006).

Table 1: Participants in the empirical study.

Participant	I	E	S	Role	Company	Education (u/s)	Job tenure
P1	x			Foreman	A	Graduated (u)	> 10 years
P2	x			Designer	A	Master school (s)	> 10 years
P3	x			Foreman	A	Master school (s)	> 10 years
P4	x			Production Engineer	A	Graduated(u)	> 10 years
P5	x	x		Machine setter	A	Master school (s)	< 10 years
P6	x	x		Machine setter	A	Master school (s)	< 10 years
P7	x	x	x	Machine setter	A	Apprenticeship (s)	> 10 years
P8	x	x	x	Machine setter	B	Apprenticeship (s)	< 10 years
P9	x	x		Machine setter	B	Apprenticeship (s)	< 10 years
P10	x	x		Machine setter	B	Apprenticeship (u)	< 10 years
P11	x	x	x	Machine setter / Foreman	B	Apprenticeship (u)	< 10 years
P12	x			Process Owner	B	Apprenticeship (s)	< 10 years
P13	x			Foreman	B	Master school (s)	> 10 years
P14	x			Technical salesman	B	Gratuated (s)	> 10 years
P15	x			Technical salesman	B	Master school (s)	> 10 years
P16	x			Construction Engineer	B	Gratuated (s)	> 10 years
P17	x			Technical salesman	B	Gratuated (s)	> 10 years
P18	x			Production Engineer	B	Gratuated (s)	> 10 years
P19	x			Quality Engineer	B	Gratuated (s)	< 10 years
P20	x	x		Foreman	B	Apprenticeship (s)	> 10 years
P21	x	x		Machine setter	C	Apprenticeship (s)	< 10 years
P22	x	x		Foreman	C	Master school (s)	> 10 years
P23	x	x		Machine setter	D	Apprenticeship (s)	< 10 years
P24	x			Production Engineer	D	Gratuated (s)	> 10 years

I: Interviews, E: Eye-Tracking, S: Shadowing. Education (u/s): Education (unspecialized/specialized)

[7] Cold-forming is a process where metals are forged at near room temperature. The contour of the forming is predetermined by tools in a bending machine and the temperature during forming remains below the metal's recrystallization temperature (VDI 3430, 2014).

The interview transcripts, field notes and eye-tracking recordings were subjected to Thematic Analysis, which entails a set of well-established steps involving open coding of the media excerpts, systematic revision of the coded segments, and identification of code-families and their relationships (Braun and Clarke, 2012). This enables elaboration of a deep understanding of the explored contexts and/or phenomenon (Ayres, 2016; Braun and Clarke, 2012; Gibson and Brown, 2009). The findings from different data artefacts were triangulated to ensure their *trustworthiness*, a quality criterion for qualitative research (Bryman, 2008). Below, we present the themes uncovered in this analysis. Description of the workflow presented in section 4 is derived entirely from our field notes. The findings stemming from it have been checked against the interview and eye-tracking data, which are occasionally presented through the section in the format of quotes or vignettes so as to ground the findings in concrete detail. The materials presented in section 5 are mainly based on the interviews carried out after the shadowing sessions, which were informed by our observations during the shadowing sessions themselves.

4 THE RELEVANCE OF KNOWLEDGE IN INDUSTRIAL SET-UP

Industrial set-up is a process involving a set of preparatory actions on a machine or a tool prior to the start of a production cycle. It happens between the end of the serial production of one article and the start of the serial production of a different one. This is a core and time-critical process from an economic perspective: without set-up there might be no production (Voigt, 2016; Van Goubergen and Van Landeghem, 2002).

Set-up can be carried out by a single machine operator (as it was in Companies A, C and D) – or by two or more operators (Company B). The latter usually pertains to larger machines. For this paper we decided to focus on single machine operator set-up as we observed that issues of knowledge and expertise sharing, which are our central interest, are more salient in this set-up scenario.

Set-up, we quickly discovered, is a knowledge-intensive process, relying mainly on experiential – or experience-based – knowledge. The literature indicates that such knowledge can be both highly personal and very difficult to capture and share (Matthew and Sternberg, 2009; Nonaka et al., 2000; Randall et al., 1996).

4.1 Industrial set-up for rotary bending

Rotary bending is a manufacturing process involving the use of specialised press machines that can be customised for the production of different articles through the set-up of a complex tool, known as the rotary draw (see Figure 1). The process usually unfolds as follows: first of all, a semi-finished product is fixed between an outer and inner clamp die. Subsequently the semi-finished product is curved by rotation around the centre point of a bend die, with a pressure die stabilizing the straight section of the pipe in front of the actual forming area. A collet guides and pushes the pipe in the forming direction, whilst a wiper die reduces the formation of wrinkles on the inside of the tube and a mandrel avoids necking of the tube by supporting its inner stability (VDI 3430, 2014).

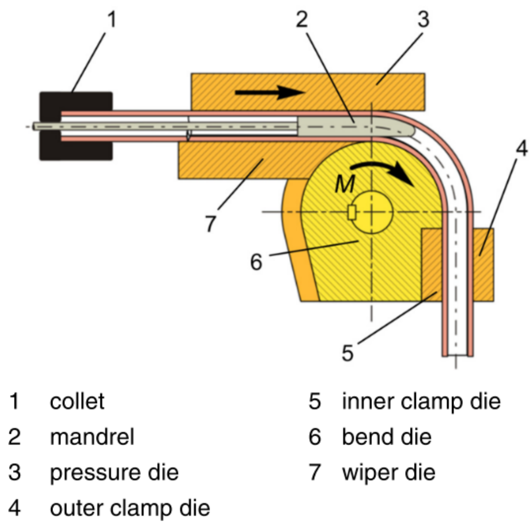

Figure 1: Tool components for rotary draw bending processes (VDI 3430, 2014)

The set-up of the rotary draw involves the assembly and disassembly of its several components on the machine (see Figure 1 and 2) and demands the use of screwdrivers, clamps and several other hand tools, which supports the manual procedures carried out by a machine operator, also known as setter or installer. Logistical and other preparatory activities such as transporting the components and the tools for their assembly and disassembly, also form part of the set-up, as we will see. In addition to that there are the positioning, movement and adjustment of the individual tool components through the configuration parameters in the control unit of the machine. Through these actions installers attempt to reach the point where all the tool components perform their functions satisfactorily, so to delivery of a curved tube – e.g. a chair leg – without any visible problems – e.g. wrinkles or cracks. This process is formally considered to be a tool-dependent cold-forming process.

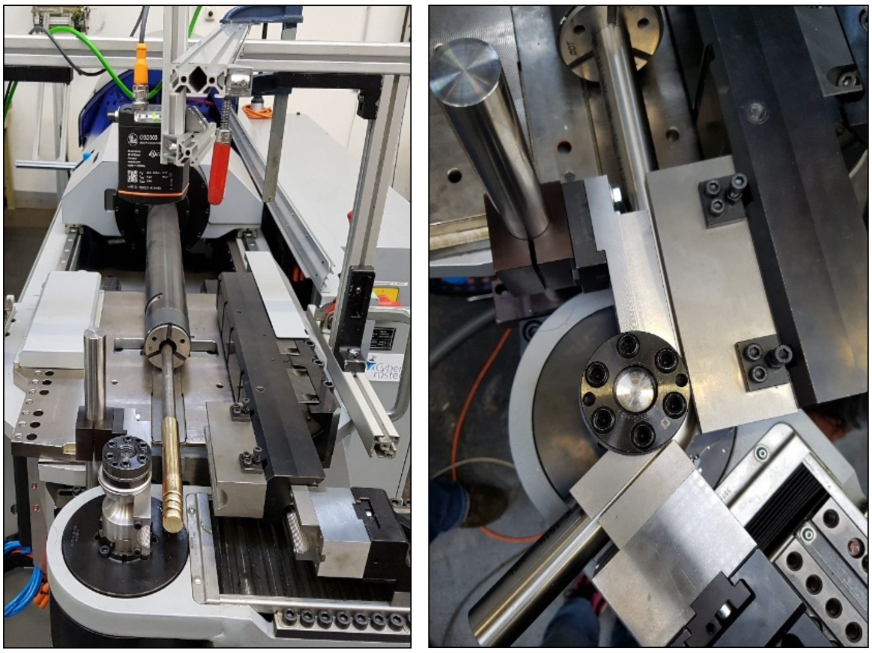

Figure 2: Mounted tools on a bending machine (Credits: UTS_Linda Schulte)

4.2 Talking planning and logistics

Set-up usually starts with procedures based on a production order. This provides, amongst other things, details about the item to be produced and the machine to be used in its production.

Using the article number, workers compile a list detailing the set of tools and machine parts required for the set-up. This list is based on a list of parts for bending a particular product associated with each machine. However, these lists are not always up-to-date. Moreover, workers could not say whether this information exists for every single product they work on:

> We have created this set-up data once for the MEWAG machine, so that people know which tool belongs to which type and which place. I then supplemented it with this type. In the production area we have a corresponding list - at least on the electric machine. I also did it for the hydraulic machine. (P2, Interview)

Here we have an issue of available knowledge. The quote suggests that there has been an attempt at sharing knowledge about which parts could be fitted to a particular machine, although it became clear that this initiative has not been sustained. Our data suggests that this list needs to be a living document, because new machine parts are designed from time to time to replace old ones and optimise the bending process. Given the unreliability of the data in the list, machine operators have to draw on experiential knowledge to elaborate the list effectively.

> The main problem is that no tools are complete. We have to assemble a tool from two or three other tools. [...] The setters do not have that much experience. This is very complicated for the setters, so they have a lot to think about. You have to think about which tool needs to be adapted. And you lose a lot of time. (P11, Interview)

As they continue with compiling the list, the location of the individual tools and machine parts becomes highly relevant. We uncovered recurrent problems concerning the storage of tools and parts. Most importantly, identifying the appropriate parts for the set-up is usually a non-trivial task. Some parts are very alike and it is difficult to tell them apart. Therefore, *knowing what* is necessary for the set-up, *knowing where* to find the relevant parts and *knowing that* a part is really what is necessary for the set-up have been identified as some types of local knowledge needed for a successful set-up process. Having this knowledge allows workers to quickly assemble the components they need to get underway, so it impacts positively on the time performance of the workers.

4.3 Assembly and disassembly cycles

Once the list is ready, workers physically gather the tools and parts. These are usually collected in a trolley and brought to the machine. Our observations showed that sometimes the required tools or parts are already in use. It was very common for machine parts to already be mounted on the machine to be used for the production order in question, or else on other machines that were currently in the middle of a production cycle. This causes logistical issues. Yet again, *knowing that* and *knowing where* come strongly to the fore. Devising ways to give this information in advance would save workers valuable time and contribute towards the efficiency of the set-up operation.

Once at the machine, workers make room for the set-up. Sometimes they have to slightly adjust a machine, so that they can access all the points where parts must be removed from or attached to. This particularly relates to local knowledge and embodied practices.

After adjusting the position of the machine, workers proceed to disassembling its current configuration, so the new one can be assembled instead. Sometimes parts already in the machine can stay where they are, so workers do not always need to remove all components from a configuration to start another. It varies as to whether they just need to swap two parts or remove several before a new one can be fitted. The decision on which parts should stay and which ones should be removed is based on experiential knowledge, which differs from worker to worker. However, our informants acknowledged that there are always improvements that can be made:

> I've been in the company for a little over two years now, and I've come to the point where I master the manufacturing cell F-03 very well. And there are still tricks that my colleagues who are here for 15 to 20 years can tell me - and they do. I just have to ask questions. This also applies to the operators. The operator also knows tricks that can be passed on through experience and questions (P5, Interview)

Experience, then, teaches workers the shortcuts that can be taken and how the set-up can be optimised. Here, in contrast with the previous situations, we move towards an issue of expertise sharing: sharing the 'knowledge of how' to best accomplish a task. Evidently, sharing this kind of expertise could help novice workers enormously:

> Only the practice keeps you going - try, try, try. The experienced are the best employees. They understand everything faster. Anyone can study theoretically, but in practice, that's something completely different. (P8, Interview)

In fact, we sometimes saw workers become so dependent on the knowledge of other colleagues, that production could be delayed if they were not around. P6 reported this as follows: 'the [set-up] order is only determined on the basis of experience…The segment leader has been familiar with this for a long time. When he is on vacation there are always problems' (P6, Interview).

Acknowledging the importance of such knowledge, some participants raised the issue of making available documentation that could enhance productivity:

> Productivity would certainly be present if a set-up guide were already available and if this guide could then be presented through a tool. The tool should again be fitted relatively easily for the single machine. So I can say then: 'I only mount the tools, but the whole guide is already there'. For my sake, on an iPad or whatever. (P4, Interview)

Assembly is guided by the list of defined tools and parts collated before the actual set-up starts. However, there are no guidelines regarding what to disassemble in the course of the set-up. Parts must be mounted in the exact location on the marked machine axis. These steps are also deeply rooted in experiential knowledge:

> The hole must be in the middle, the bow must be clean, there should be no scratches on it. And now it has to fit into the template here. Distances at the beginning and at the end must lie within the markings. He has to fit in all the cams. The end must not be farther back than the first stroke and the white stroke here is the longest run. So, now I can start the system and continue to watch the first 15 minutes, because there is still something to do. (P5, Eye Tracking)

The information needed can only be found in manuals with difficulty. The knowledge is embedded in a workers' routine and so needs to be understood and deployed contextually. Nevertheless, these tricks and tips, subtle though they are, are deeply relevant to efficient and speedy set-up.

The alternation between assembly and disassembly of parts continues until all new parts are fitted in the machine. It is important to note that sometimes assembly is interrupted for other reasons. Sometimes workers forget to include important tools or parts in their initial list. Sometimes set-up is interrupted by colleagues coming over to ask for help with the set-up of other machines. Sometimes, managers tell workers to stop a task and attend to more pressing matters.

Operatives argued that recording interruptions arising from problems, breakdowns, solutions and work-arounds, was important for others to *know about* as a source of learning:

> That would perhaps help us for those who do not yet have a comprehensive technical background. You will then be introduced to the matter faster. You might as well take a quick look ‘Ah, there's the problem I've caused. (P1, Interviews)

Industrial set-up currently can, and often does, lack systematization, and is mainly based on the experience and ‘know how’ of a respective machine operator. Disassembled tools are temporarily stored, often chaotically, in a trolley and only properly put away after completion of the final adjustment of the machine program.

4.4 Programming and adjusting

Once the assembly of the parts ends, it is time to work on the machine program, which is already stored in the machine controller. Workers usually interact with the program through a touch screen display or through a remote control-like device. This part of the set-up process is highly dynamic, characterized by constantly changing settings on the machine. In the age of computer numeric controlled (CNC) machines, corrections are made primarily in the program code of the controller. In cases of a control deviation between the bending component (actual value) and the drawing (set value), operators act as regulators by independently determining the manipulated variable from the observations made – see Figure 3.

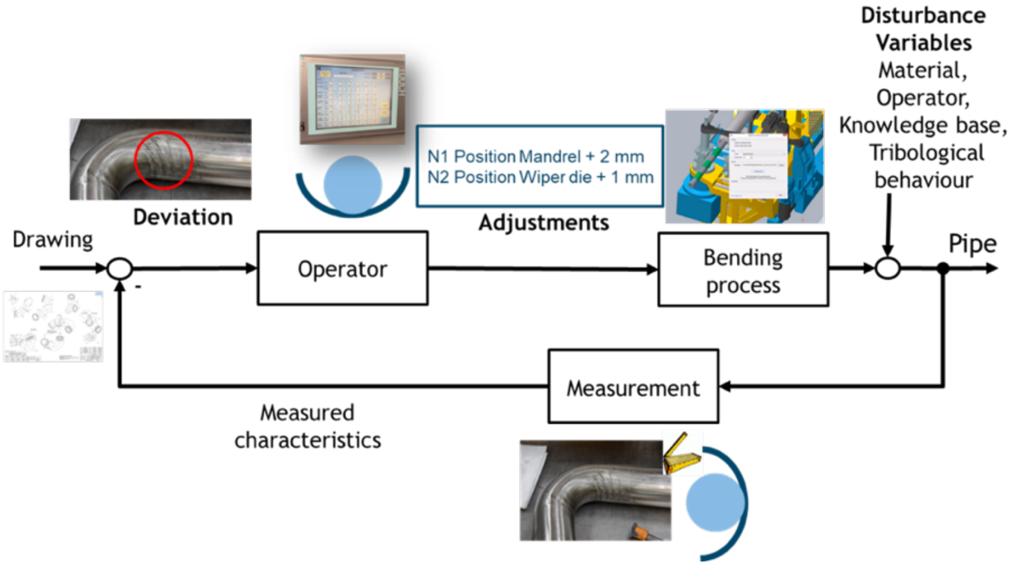

Figure 3: Human in the loop of the set-up process.

The dynamics of the set-up process are largely caused by the existence of fluctuating disturbance variables. These can be due to creeping influences, such as wear, or to ad-hoc matters such as changing material parameters. Machine operators rely heavily on their experience for the correct interpretation of measured values and visible phenomena. Their efforts lead to a definitive set of parameters, which are stored as correction values within the CNC program. At this point, it is possible to see a discrepancy between the inaccurate information – on the basis of which the corrections take place – and the need for very precise settings in the CNC code. Figure 3 shows a correction of pleats on an inner pipe bend. The machine operator recognizes this issue and defines the manipulated variable. In this case, the operator changed the position of one machine axis by 2 mm and the position of another axis by 1 mm. However, he was unable to explain the cause of the problem. Corrective actions like this can take up half of the actual set-up time and even lead to interruptions during actual production.

Parameter adjustments are usually made according to information acquired through practice:

> The segment leaders in the production area are so fit that they can already see by the colour of the material whether it's a harder or a softer material. And they also know that they, then, have to change the parameters. Either way, they notice it. I do not want to believe that at first, but I see a difference in the meantime as well. I do not know if it's hard or soft, but I recognize the difference. (P2, Interview)

Our findings suggest there are so many parameters they could not possible be kept in a physical catalogue for operator support during set-up:

> There are many parameters involved. For example, if I have materials between 530 Newton and 640 you'll hear it yourself, there's a huge difference. And watch every single step. How do I want to hold on to that? If you could program a machine like that, others would have done it before. This is still missing in bending technology. This was a three-roller bending machine that should automatically deliver. It was then determined that the machine has done everything. She bent the one part for hours. It did not work. We did not get the radius it should have. That did not work. Due to the material deviations. (P5, Interview)

Once the parameters are set, workers go on to test the results of the set-up. They typically take one of the pipes that will go into the production cycle, bend it and carry out a visual quality test. First, they look for visible irregularities in the bend, e.g. cracks or wrinkles. Then, they put it in a testing mould to make sure that the resulting angles are correct. If the pipe is of sufficient quality, the set-up process is finished at this point. However, we found that workers seldom get it right at the first attempt. A series of adjustments are usually necessary, through which workers deal with the correction of dimensional deviations. The machine interface is used to change the paths and angles of the bending axes. To facilitate this, the exact position of the deviation is detected first of all. With this information in hand, the relevant line of the machine code is selected and a correction parameter is entered. After this, the bending process is re-run and the resulting tube is again subjected to a gauge test. This process is usually repeated several times because the parameters influence each other in unpredictable ways such that, following a correction, various other portions of the tube have to be corrected as well. This creates an overhead of lost time and wastes material, as a new pipe has to be used for each test.

All of this is heavily based on the installer's experience and related information is not kept anywhere in the company. In one eye-tracking session we observed P5 working on adjustments to the machine programme. He went to the correction window, and changed the value from 1.3 mm to 0.8 mm. This decision was taken after a brief glance at the component in the gauge. As one of the values had been adjusted by 0.5 mm, this cascaded to the others values as well.

In another eye-tracking session, P6 recounted his reasoning as follows:

> I then go to my programs. Here are my individual bending programs [a multi-step program]. I now consider which individual bends I adjust. This is the last 90 ° bend of the part. This is the process number 7. It is now over bended to 0.5 °. But I want to turn it up a bit, that is, we'll set it to 0°. I save my change again and drive the machine into the basic position so that it picks up the data. And now turn the next part. (P6, Eye-Tracking)

There is evidently a great deal of 'know how' embedded in the observed assembly/disassembly cycles, knowledge that is not easily recovered. We noted that less experienced workers needed more time to make adjustments and wasted more production material on tests. So, assuming it can be accomplished without incurring other costs, the sharing of this embodied knowledge and expertise amongst workers would be of evident value to this kind of enterprise.

5 KNOWLEDGE AND EXPERTISE SHARING CHALLENGES IN INDUSTRIAL SET-UP

Fostering knowledge and expertise sharing is widely acknowledged to be an investment in a company’s competitiveness (Schmidt, 2012; Gupta et al., 2000; Ackerman, 1998; Howells, 1996). During our investigation, participants consistently referred to the importance of promoting practices of knowledge and expertise sharing. However, there are clearly several obstacles to accomplishing this.

5.1 Strategies for knowledge and expertise sharing and associated difficulties

The primary source for knowledge and expertise sharing in our companies was training. According to our informants, new workers have to undertake training before being allowed to engage in set-up. Segment leaders, who usually have 2 years plus of experience in the company, are responsible for introducing new workers to the work procedures and for providing them with all the necessary information:

> [Training] courses take place here in the house. Either internally or externally. Then there will be a briefing by a colleague - usually a segment leader colleague who is already experienced in the field. They also do it very well. I can only confirm that. The information that has to flow also flows. But there are many questions that need to be considered. And these questions only come up in the course of time. (P5, Interview)

Although training is necessary, it is not sufficient. Set-up, especially programming of the machine, ‘is a very complex process. You have to know a lot already. There is a lot for newcomers to learn!’ (P6, Eye-Tracking). Unsurprisingly the didactic practices of segment leaders are based on demonstrating the actual job, not on verbal or written descriptions alone:

> When I teach [people], I take [them] with me when I rebuild. I tell them, 'Here are the parts. If you cannot figure out which parts go where, you have a list here. 'Then I do the set-up with them four to five times. At some point, I say, 'I showed you this a couple of times. Now you do it yourself '. Of course I'll go with you, check and see how he gets started. What does he do? That actually works pretty well. This worked very well for a colleague. (P7, interview)

But even the most willing trainers can forget to mention relevant issues. One possible reason for this is the fact that there are things that are so ingrained in their practice, they tend to perform them automatically, without reflection:

> People are different. The only problem I see is that… There are people who teach others by showing exactly how the process happens. [They will say:] 'Then you have to pay attention here. Then you have to pay attention to that'. But there are also people who take some things for granted, because they are 20 years and then forget to mention… Even minor details. And when a situation comes up [they will say] 'Oh I forgot to tell you that ...'. If you ask a colleague who has been here for some time, he also likes to pass on his knowledge. (P5, Interview)

An alternative to personal transmission of knowledge and expertise is learning through existing documentation, such as the photo album discussed by Schmidt (2012). However, in this case, documentation has proven to be less than adequate, partly because there is little motivation to keep it properly updated. Instead, knowledge tends to be concentrated 'in the heads' of very few actors:

> [...], there is just a lack of documentation so this mainly remains 'in the head' knowledge of the individual employees. If today three employees leave the company and tomorrow three new ones are hired, then a massive problem arises. (P4, Interview)

Those documents that do exist concerning set-up are usually very abstract. Often, the manuals in question are machine-, rather than product-specific. This means, they usually describe how different parts can be attached to the machine, but do not specify which parts should be used for which product, making the lives of new workers hard. These documents are also often outdated:

> The document […] was prepared at the very beginning, which was for the first few programs of the first articles. And then, with the time when we got more and more articles, the whole [set-up process] has been changed. The documentation has remained as it has been originally conceived. (P8, Interview)

As a result, existing documentation ends up not being used, and the main source of knowledge and expertise sharing remains personal exchange.

5.2 The burden of knowledge sharing and ways to relieve it

Finding the right person with the requisite expertise is not a particular problem in this context. These are, after all, SMEs and a relatively small group of people is engaged in set-up during each shift. Furthermore, segment leaders serve as a reference point, so workers do not have to worry too much about finding the right person to go and ask for help. There are also colleagues that can help with different types of problem, each one within their own area of expertise:

> We always have a segment leader, who is experienced and summoned for help by anyone. So, you are not alone. Then there are the electricians, who can help with technical problems on the robot or set-up problems with the robots. They are always available and know the important information. These men are very well trained. Of course, they are much better at programming robots than I am, at least in part. Everyone

> has their own area of expertise and they are divided according to the shifts. (P5, Interview)

There are, unsurprisingly, often tensions involved in having to repeat some sorts of information: ‘Now we have to tell the new people the written instructions again and again. This is complicated’ (P11, Interview). This includes the maintenance of tools and machines and, in the case of segment leaders, the need to carry out several set-up operations. Such repeated explanations can get in the way of the primary task. Therefore, capturing the knowledge held by these people in ways that it can be easily shared and understood is key for effective knowledge and expertise sharing. This is a question of devising the appropriate ‘boundary objects’ to transit between shifts, work groups and contingencies (Ackerman et al., 2013). Some kind of documentation is generally perceived as necessary:

> As I said, standardized set-up documentation would be important. If there is anything that must be highlighted, if it were recorded, were documented, it would be easier for everyone [to get to know about it]. That is missing completely. That's missing on all machines. (P1, Interview)

Nevertheless, a theme that strongly emerged from our data is the usefulness of building up a *common information space* (CIS) as problems happen:

> Once an error occurs, it must be written down with a solution. If I write an error and the path that led to it, it may be that the segment leader comes who has been here for 25 years and says ‘that is a piece of cake. Was totally wrong. We have to go this way’. You have to weigh that up afterwards. But you actually have to write something down to see how things are. So, everyone remembers about it and makes things differently. (P6, Interview)

If we see this problem as twofold - documenting what knowledge might be shared and identifying the circumstances in which it needs to be shared - this resonates with known approaches to expertise sharing, such Answer Garden (AG) and its sequel Answer Garden 2 (AG2). Here the issue of OM was addressed by providing an architecture to support the retrieval of recorded knowledge and to provide access to appropriate individuals (Ackerman and McDonald, 1996; Ackerman and Malone, 1990). However, time constraints and 'ownership' issues often over-step such solutions.

5.3 Technological challenges

Our analysis suggests that there are possibilities for CPS to support knowledge and expertise sharing. One possible direction, according to the participants, is support for recording the practical steps undertaken during the set-up process. One participant also said:

> [Knowledge that we cannot write down directly] is very important for the set-up. This knowledge you learn during the practice. So, the new employees are watching and you do not need to write anything for the bending machine because the programs are there, all programs are stored on the computer. You choose the right program, what you should produce, otherwise you do not need to know anything. You have to be careful to select the right program, because if the pipe length is 500 [mm], you cannot choose 1000 [mm] as length. Of course, if the length is 1050 [mm] and the program chooses only for the length 1000 [mm] then there are problems at the end of the bending process. (P10, Interview)

So, local knowledge embedded in practice is very important for set-up operations. There is an expectation that, if this type of knowledge is recorded and shared, the costs of training will reduce and efficiency and effectiveness increase. However, it is not just a matter of recording the data, but also of showing it in appropriate formats. For instance, one of the participants raised the issue of data visualization:

> The central thing is the material characteristics. Nowadays, a simulation is still not able to say that 'you have to adjust the axis by 2mm'. Simulation is not able to say that. But the simulation can clarify physical connections to me. It would be desirable that it could say 'The physical relationships in this bending machine are so.' If I can operate it, I am automatically at that level and can represent the physical connections. (P5, Interview)

Again, the central issue here is that embodiment is not easy to represent in terms of propositional content. As we have seen, video provides a way forward for ethnographers interested in work practices, but new technology affords a more sophisticated set of possibilities that might provide for the more specific needs of inexperienced practitioners. The sheer delicacy of alignments, such that, for instance, adding or deducting 1 or 2mm from a particular configuration makes a difference to the adequacy of results, seems to indicate the use of sensor technology as a possibility. We will elaborate on this in our discussion but, to conclude, we present the view of another participant regarding how technologies that could record and share 'know how', 'know that' and many other types of knowing embodied in action could revolutionize the sharing of knowledge and expertise:

> If you had a novice now, where you would say 'I'm not showing you how to do that. You do it!'. For example, you have a small tool trolley, there is an iPad on it and what you have filmed with me, that you would do it in a more extensive or longer form, where people see [he looks away and takes some the tools] and knows exactly 'I have to take this' or 'put it into the box' and if I build this in the order… every idiot must be able to do it, to accomplish at least a set-up. Changing values and parameters is again a matter of experience. If it's purely about the set-up process of the machine, that one can

> say ‘I'm watching. I have to do it that way. I have to make that up. Or ‘that has to be done’. But that is for the absolute novices. (P7, Debriefing interview after first eye-tracking session)

6 DESIGN IMPLICATIONS

The findings above indicate the sheer complexity of the knowledge and expertise sharing problem in the explored context. As we have seen, there is a fairly substantial literature dealing with the possible application of CPS across various domains. Few, if any of the studies in this literature, however, base their design on the kinds of detailed qualitative study we have engaged in, nor have they dealt with the possible application of such systems to set-up work. Below, we suggest ways in which studies of this kind can inform the configuration of CPS in industrial settings of the kind we have examined – settings that are still underrepresented in the CSCW and HCI literature. At present, we would not claim to be at a stage where we can present a worked-through design solution to the knowledge and expertise sharing issues we raise above, but this is not in any case our intent. Our point, rather, is that solutions to problems of this kind require us to know exactly what kind of problem we are confronted with, and why it matters. We have shown how, for reasons of both time and money, it does. CPS, if they are to constitute a potential solution, need to offer more than the presentation of simple information or instructions. These are already amply visible in the literature (Wang et al., 2014; Zhu et al., 2014; Pathomaree and Charoenseang, 2005; Klinker et al., 2001), but do not seem to be sufficient, according to our findings, to enable expertise sharing in the level of detail required by an operator. The point, we feel, is to convey ‘know how’ as well, with the aim, for instance, of enabling an installer to have adequate competence when dealing with tolerances of one or two millimetres. Moreover, as instructors may themselves be heavily engaged in the day-to-day business of production, any solution will need to recognise that there is a time-critical element. Thus, the technology must be able, during the set-up process, to provide adequate, relevant and timely information in sufficient detail that it can reliably inform operatives of the subtle and complex manoeuvrings that may be necessary in a set-up process. It should also constitute a repository that can be used both for the acquisition of information and as a basis for training, insofar as some of the knowledge *is* of a propositional kind. At present this kind of information is: 1) not always up-to-date and well maintained; and 2) not always easy to find.

There is an established literature that points to how apprenticeship models encompass features of 'learning by doing' (Lave and Wenger, 1991). Thus, over time, operatives do learn the manipulations necessary for effective working by copying others. However, this requires a physically collocated workspace (Tang et al., 2007). The set-up process described above often does not allow for learning of this kind to take place, because the necessary experience and expertise is not always immediately available.

Whatever system is envisaged, then, it has to cope with some evident challenges. In our view AR technology, in combination with appropriate sensory input values and, where appropriate, codified information about tooling and other material properties, can help overcome many of the difficulties we have discussed. Any effective technology, here, will have to deal with the following three main issues:

- *Design for timeliness.* As we have seen, expertise is relatively scarce in this environment and error is costly. Any solution will therefore need to deliver relevant information in a timely way with minimal prospect of error. Some of the relevant information will be codifiable (e.g. parts and machinery that are pertinent to the task) but the repository for this information will have to be easily maintained, up-to-date and capable of providing contingent information as and when required. In other instances, seeing an experienced operative do the assembly will be the best solution available.

Here, providing a granularity that reflects the subtle judgements made by experienced operatives is best done by managing sensory data input.

- *Design for appropriate visualisation.* Capturing and reproducing instructive material still requires decisions about the position from which the process will be observed. Findings from the literature suggest that capture in this case is possibly best done from the first-person perspective, although further research is still necessary (Fussell et al., 2003). Head-mounted applications are especially well-suited to the set-up of new parts and materials, as they allow workers to use the two hands. In these situations, every move may contain essential information. Capturing complex set-up instructions in a stepwise fashion using short video sequences from a first-person perspective can offer effective support for the visualisation of particular actions that need to be carried out.
- *Design for the contextual use of sensors.* Physical processes need to be rendered by measuring potentially tiny deviations from target processes. Capturing small tolerances through sensory data input is a promising solution, especially since it has the potential to reduce error. Sensors can reduce uncertainty through workspace monitoring, thus increasing the effectiveness of instruction by preventing errors and reducing stress (Miller and Swain, 1987).

Just one option that might meet the above requirements, and that we are currently exploring as an early prototype, would be a set-up editor developed for the Microsoft HoloLens. The basic functions of this device can be subdivided into two areas in a way that might allow for effective knowledge and expertise sharing.

The first area would comprise a recording module. This would enable an expert to record and demonstrate the set-up process with short video clips and other media such as photos and voice annotation. As the HoloLens is a head-mounted device with a built-in camera, this would allow for the capture of embodied actions from the perspective of the installer. The AR aspects of the technology can then be drawn on to ensure appropriate contextualization of the information by showing the exact installation location on the real machine (see Figure 4).

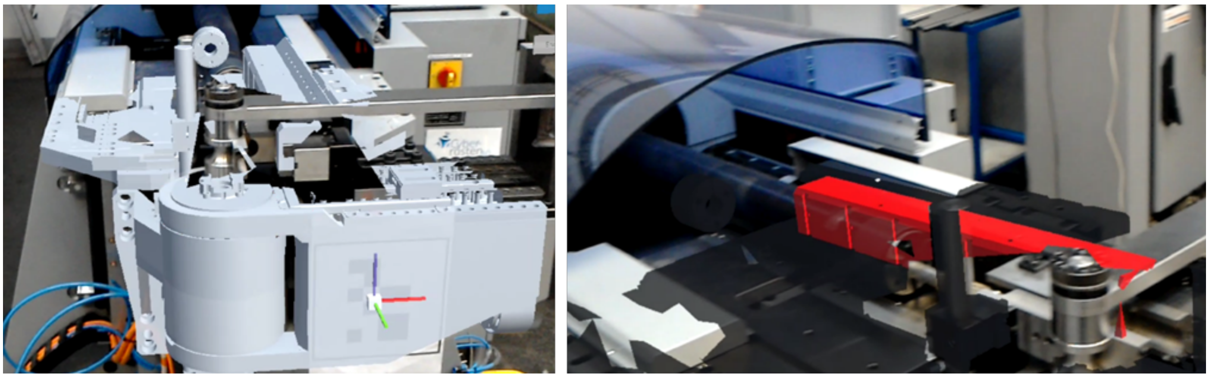

Figure 4: Contextualization of set-up instructions by marking the assembly sites on a bending machine – e.g. the green, blue and red axes on the left picture and the red area on the right picture.

The second area would include a playback module where the set-up instructions could be displayed in a context-specific way and enriched with sensor values. For this, the installation location can be marked (see Figure 5) and a video sequence of the set-up instructions displayed. The installer could then independently navigate step-by-step through all of the set-up instructions whilst maintaining access to all the required assembly components and assembly aids.

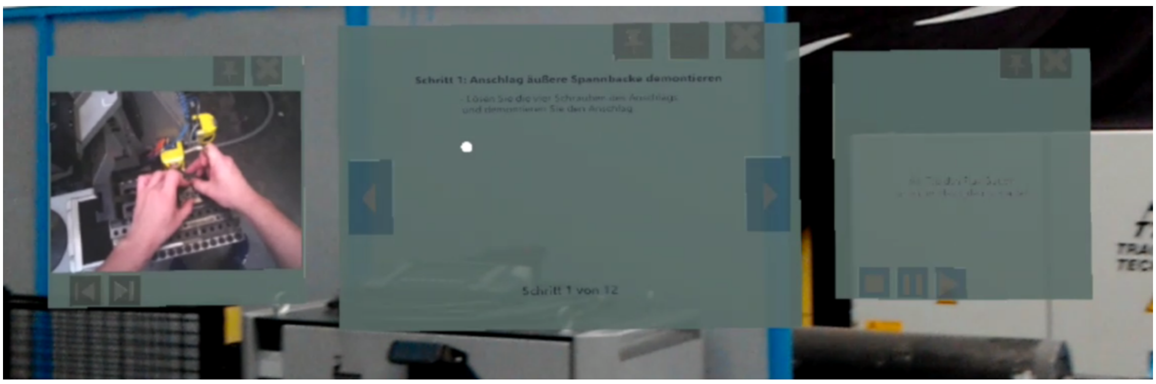

Figure 5: First prototype of the playback module running set-up instructions

Sensors can be used here in two critical ways. First of all, position sensors can be used to measure the displacement of tools and certain machine components. The results can then provide an indication of the outcome of different actions, contributing to a deeper understanding of the process. Mistakes due to the incorrect mounting of tools, or even the presence of a wrong tool, can be detected by the sensors. To do this, contactless measurement can be accomplished by means of a 3D camera. This can reliably detect dimensional deviations independent of light and dirt conditions (in the left-hand picture in Figure 2 an installed camera can be seen at the top of the picture).

As suggested by related work, AR is likely to make formal training less necessary and can be used directly on the job (Neumann and Majoros, 1998), although there is still a need to engender trust in its applicability to actual activities. In relation to this, AR can locate information in a specific milieu and imbue it with specific contextual relevance. It can also render the information quickly and easily accessible, thus reducing any inhibition threshold regarding its use (Neumann and Majoros, 1998). Nonetheless, certain situational characteristics will remain absent. These include environmental conditions. However, in the described deployment these can be detected by sensors, for instance, the location of the tools on the machine or the bending of the machine under a load. The trustability of the provided visualization delivered by the use of sensors and description of the situational parameters in conjunction with the AR technology, can result in a comprehensive artificial collocated workspace. Together these elements can make it possible to integrate embodied action into the expertise sharing process for set-up tasks.

7 DISCUSSION

The data presented across sections 4 and 5 shows that, when it comes to industrial set-up, several kinds of knowledge come into play. In so doing, the dichotomy found in much of the

KM literature between ‘tacit’ and ‘explicit’ knowledge, or ‘know how’ and ‘know that’, does not suffice to understand the practices involved. As Schmidt before us has argued (2012), there are not just two categories of knowledge, but ‘knowledge of different things’ (ibid., p. 214), which involve not only ‘knowing how’ and ‘knowing that’, as proposed by Ryle, but also ‘knowing what’, ‘knowing who’, ‘knowing where’, ‘knowing when’, and so on. Thus, in this paper we have sought to decompose ‘knowing how’ and ‘knowing that’ into finer elements, with concomitant proposals concerning technological support for sharing.

Our findings suggest that practiced practitioners are so embedded in their routine work that what seems rather mysterious to outsiders is, for them, utterly mundane and obvious. As a result, some things get taken for granted, which is likely to impact negatively on knowledge and expertise sharing. This calls for solutions that allow ‘taken for granted’ local knowledge to be shared with others. Furthermore, since much of this knowledge is embedded in reasoning that is manifest in closely sequenced activities, it would seem that methods for displaying those sequences in similar detail are appropriate. At the same time, the critical point here is to identify what explanations are being used, what purpose they have, why it is worth articulating them, and how they can best be represented. We have suggested above that the problem for inexperienced workers is akin to the problem faced by ethnographers in their need to capture the detailed and meaningful aspects of work practice. In the last few years there have been notable improvements in, *inter alia,* video technology that have provided for increased granularity and better rendering of the subtle and sometimes overlooked features of collaborative work. It remains the case, however, that some aspects, especially haptic and judgemental elements, are still difficult to recover. In addition, unlike ethnographers, operatives and the organization as a whole face significant overhead in terms of time taken, errors made and resulting costs.

Put simply, we are dealing yet again with a practical problem concerning how workers can actually share expertise that is embedded in what they do, and that it is extremely difficult for them to know how to explain when confronted with someone who is not equally invested in such practices. This is only compounded by having to provide explanations as they 'go along'. Explaining is a secondary task, not a primary one. So then, new technology might, with maturity, provide opportunities to dissolve many of these issues related to the distinction between 'know how' and 'know that', whilst also affording other kinds of knowledge sharing.

There are two general issues confronting us. The first one is that this knowledge is local, situated and used in contingent situations. Thus, it only exists within the situations in which one tries to explicate it. The second concerns recipient design (Sacks, 1995). Here knowledge and expertise sharing depend on the relationship between the actors involved. Our data provides evidence that the level of detail or the willingness to share a particular piece of knowledge changes according to the recipient.

To the best of our knowledge, these two issues are usually handled separately in the literature, whilst our data suggests that they are actually interlocked and ramify from one to the other in various subtle ways. Our findings suggest that we need to find mechanisms to overcome the various overheads entailed, so that knowledge and expertise sharing can effectively occur. This is becoming a pressing commercial issue, because companies – especially SMEs –need to ensure that knowledge and expertise sharing flows in a timely and accurate manner (Hau et al., 2013; Pipek et al., 2012; Nonaka and Von Krogh, 2009; Gupta et al., 2000). As one respondent above suggested, currently knowledge is usually concentrated in the hands of a very few actors. When these actors are for any reason no longer available, say due to ill-health or new job opportunities, a company can be faced with serious difficulties.

So, our aim in this paper is to move a step towards reframing the problem of knowledge and expertise sharing in CSCW. We argue that conventional knowledge transfer models do not suffice to handle what we have observed in industrial contexts, since they do not tackle the embodied work that we have shown to be decisive for effective knowledge and expertise sharing. Our findings here suggest that much knowledge and expertise can be shared by simply observing in adequate detail the embodied action in which practices are embedded.

Much of the data we presented concerns haptics. The work witnessably involves the use of hands, the measurement of pressure and speed, the identification of angles, and so on. The potential for CPS here is evident, because sensors can provide precise haptic information. It is therefore likely that sometime soon embedded sensors will capture certain aspects of practices that are typically described as involving 'know how'. Our argument is that we should take advantage of the affordances of such technology and utilise it as part of a knowledge sharing system. This may well also support workers in dealing with other challenges, such as locating and/or identifying the right parts needed for a set-up process, avoiding time being lost in using incorrect parts that at first sight seem to be correct.

As discussed in our findings, there are parts that differ from each other only very slightly due to the angle or due to millimetre differences. In the case of bending, 1 or 2 mm can make an enormous difference. The discrepancy between a lack of accuracy in the available information and the need for very accurate settings can potentially be addressed by CPSs which, integrate the sensor technology we outline above with (possibly) augmented reality information. This can potentially provide additional information for the man-machine control loop (Gellersen, 2005). In so doing, the decision criteria, on the basis of which the setter defines the correction parameters, is widened. Specifically, this means that non-visible physical processes are made visible to the machine operator through the use of sensors (Chong et al., 2003). This might ensure that the trial-and-error phases are shortened and that the success of the set-up is achieved more quickly.

At this point, we argue that sensors that are integrated into a CPS can play an important role in the knowledge sharing process. Sensors can provide targeted information about discrepancies. A simple example is a temperature sensor. This provides accurate temperature readings at one point in the process. By combining this information with the results of the bending process and establishing correlations, the installer can use this information to set the parameters more quickly in future bends. As part of a CPS, however, sensors are only part of the story. Only the visualization and contextualization of the sensory information represents a relevant added value for the machine operator. To be useable the measured values also need to be processed in an easily understandable manner and displayed in the correct context. Due to the dynamic nature of the setting, real-time systems are advantageous since data can then be accessed without significant delay. Thus, the machine setter is able to allocate the measured values to the part produced, based on the knowledge and expertise shared through the values collected through the sensor technology embedded in the CPS in use. Note in particular how this is embedded within the ongoing accomplishment of the work, rather than demanding overt explication. This addresses both problems of capture and the accountability of person-to-person sharing.

To conclude, the use of AR provides another layer to enrich this knowledge and expertise sharing. Through the use of AR systems, workers can potentially see visual digital representations coming, for instance, from a simulation at the same time they observe the physical machine and parts. This, we argue, has considerable potential to improve the accuracy and timeliness of information and expertise sharing.

8 CONCLUSIONS AND FUTURE WORK

Past and current CSCW research, visible in the thorough literature review provided by Ackerman et al. (2013), both show that expertise sharing remains a relevant and timely topic but also that the character of systems to support it will depend on the domain in which they are inserted. CSCW, as yet, has spent relatively little time in the investigation of manufacturing contexts in which such systems might play a significant role and here we have provided some initial results which, we hope, might prompt future research.

We argue that we have whole new ways of recording movement, the haptic, and other types of embodied action, and aligning it with propositional content via AR and sensor technology. This is to-date largely underexplored to our knowledge and has huge implications for the way we think about sharing expertise and knowledge. A first attempt towards a discussion such as the one that we presented here has been made by Ludwig et al. (2017) but the empirical data we provide here adds force and valuable nuances to the argument.

With this paper, we take a step forward in reframing the problem of knowledge and expertise sharing. We argue that we are about to enter a third generation of research in the matter and as future work, we set out to pursue this strand of research, especially in regard to the process herein explored, i.e. industrial set-up. Following the premises of the DCS framework (Wulf et al., 2015), we have already started with the design phase of our initiative and carried out a couple of design workshops with our participants. In this phase, we are focusing on the design and implementation of a CPS for knowledge and expertise sharing in industrial set-up, following principles of participatory design and evolutionary development. As soon as we have a stable functional prototype, we will engage in a technology appropriation study. In so doing, we hope to be able to uncover further challenges concerning this third generation of CSCW research on knowledge and expertise sharing.

In particular, we call for research on the challenges associated with the use of CPS. Despite the great potential of these systems, the literature has already identified challenges concerning its use, which go from difficulties in handling new interaction principles to ergonomic problems due to the use of certain devices, e.g. AR glasses (Paelke and Röcker, 2015; Monostori, 2014; Lee, 2008).

It is worth pointing out that, although our findings provide a detailed account of the practices of machine operators carrying out set-up processes, they are not immediately generalisable. However, we are confident that our findings about the need to balance information about 'know how' with other forms of knowledge and record it via new technological affordances holds promise on a more general level. e.g. in the context of set-up of stamping machines.

Finally, the use of AR- and sensor-based CPS for industrial set-up is only one of the possible areas of application of such systems. It would be really useful to explore these issues in other contexts, so as to better understand the potentials and limitations of such technologies for knowledge and expertise sharing across a range of domains.

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