Designing Cyber-Physical Production Systems for Industrial Set-Up: A Practice-Centred Approach

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Abstract. Industrial set-up has long been a focus of scientific research, largely because it entails substantial cost overhead for manufacturing companies. Whilst various efforts have been made to optimise this process, mainly in terms of time and other resources needed to accomplish it, to date little can be found in the HCI literature about how digital technologies can support workers who engage in it. This article sets out to addresses this gap in the literature by introducing a Design Case Study carried out for the conception of a CPPS (Cyber-physical Production System) to support machine operators with industrial set-up. Our contribution is therefore threefold: first, we describe and discuss the results of an in-depth ethnographic study, carried out under the premises of the grounded design (GD) research paradigm, to uncover practices of machine operators to inform design. Second, we introduce a series of design implications drawn from those results. Finally, we demonstrate how those design implications have informed the participatory design activities pursued for the conception of the CPPS in question. In so doing, we advance the state of the art on the design of digital technologies to support people working with industrial set-up and open new research directions on the subject.

Keywords: Practice-centred Design, Design Case Studies, Industrial Contexts, Cyber-Physical Systems, Augmented-Reality, Sensors, Design Implications.

1 Introduction

Industrial set-up refers to a set of preparatory actions on a machine or a tool prior to the start of a production cycle [1]. This is a core and time-critical operation in manufacture and in many cases without set-up there is no production. Therefore, supporting it is key to maximising efficient production and to address the challenges from the trend towards decreasing order/delivery sizes and increasing the range of produced artefacts [2, 3]. Furthermore, the resulting need for flexibility stemming from increasing globalization, customer expectation, intense competition, as well as short innovation and product life cycles faced by either large, small or medium-sized enterprises for many years now [4, 5] has direct implications for industrial set-up. On the one hand, there is a need to reduce resource allocation and, on the other hand, there is a demand for ever more flexible production cycles and ever more varied quality demands [6]. This need for flexibility ramifies at a worker level too, through the demand for flexible competences to handle heterogeneous set-up processes. This may entail being able to handle a large range of different products, use a variety of materials with varying degrees of acceptable tolerance, and all of this on a number of different machines. This leads to a variety of KES (Knowledge and Expertise Sharing) issues [7, 8], which can be potentially addressed by CPPS (Cyber-physical Production Systems) [3].

A review of the HCI literature demonstrate that little is known about how these systems can be designed to effectively support machine operators in industrial set-up [3, 4]. In view of the relevance of human-centred methods for the conception of systems that can effectively support users, this article aims to contribute towards filling or, at least, mitigating this gap. To fulfil our goals, we conducted an ethnographically informed investigation in four SMEs where the goals were to better understand the practices inherent in the set-up of bending machines and how CPPS could potentially support these practices. So, the research questions that this article sets out to answer are:

1. What challenges do machine operators face in practicing industrial set-up?
2. What HCI aspects must be considered in the design of CPPS, so that the resulting solution can successfully support machine operators to overcome the challenges they face in regard to industrial set-up?

Our study is oriented towards the GD (Grounded Design) research paradigm: a praxeological worldview, which highlights the importance of understanding practices for the design of useful and usable digital technologies [9]. This is a well-stablished paradigm for HCI research, increasingly being used by the community, rooted on a pragmatic approach to design research and predicated on clear scientific practices [9–11].

Our research questions are clearly informed by GD and go to the heart of HCI. The first research question focuses on understanding practices: according to GD, clearly understanding practices is key to identify the design space for the conception of new and innovative technologies that can effectively be used and appropriated. Designing useful and useable technologies is a central aspect of HCI since its very beginning [12–14].The second research question focuses specifically on identifying the HCI aspects that would contribute for the design of usable and useful CPPS to support machine operators. With this question we set out to investigate, among other things, aspects of the user interface and the interaction with it, seeking to advance the state of the art of the HCI literature in terms of designing CPPS for similar contexts and processes.

The presented findings are based on rich descriptions of the work processes involved in industrial set-up, shedding light on the practices of machine operators and the difficulties they face with such processes. They allowed us to elaborate a set-up model to unpack possible opportunities for the design of CPPS for industrial set-up. Hence, our contribution is threefold: (1) we present an in-depth user study in manufacturing contexts, which remains visibly under-addressed in HCI and CSCW, exploring the potential of CPPS to support machine operators in industrial set-up (section 4); (2) we introduce a set of design implications, providing useful directions to follow when designing CPPS to support industrial set-up, drawing attention to important interaction challenges (section 5); (3) we illustrate how those design implications can be applied in the design of a CPPS to support industrial set-up (section 5).

2 Related Work

In this section we provide relevant background information regarding the concept of CPPS and reflect on how these systems can potentially support industrial set-up. We also examine current HCI und CSCW literature on KES, which we found to be a central aspect of industrial set-up and the challenges that machine operators face on a daily basis, as discussed in our empirical sections. It is worth noticing that this section is neither meant to cover all research studies on the subjects above, nor to deeply discuss the reviewed studies. Instead, this section is meant to setting the scene for the analytical developments of sections 4 and 5, which further elaborate on them.

2.1 Cyber-physical production systems and their potential for supporting industrial set-up

CPPS consist of autonomous and cooperative elements and subsystems, e.g. Smart Machines and Smart Factories, which are connected to one another from the process level to the production level, depending on the situation or context [15]. Their characteristic features include the networking of various production components, such as machines or tools, as well as the data sets characterizing them [15, 16]. Concrete application examples of CPPS exist in both the industrial context and inter alia in aerospace, healthcare, civil infrastructure, logistics, military or defence, automotive, energy network and agriculture [17–19].

Lee et al. [20] introduce a structure and architecture for CPS (Cyber-Physical Systems) – and consequently CPPS, which are nothing else than CPS designed specifically for production contexts – starting with data collection, moving through analysis, up until final value creation. This architecture, according to the authors, should serve as a guideline for the implementation of such systems in the industry. These guidelines are supplemented by practical applications and techniques that underpin the theoretical architecture with practical implementation possibilities. Nevertheless, the design and development of useful and usable CPPS has proven to be challenging, which calls upon further research and development in the area.

Authors such as Lee [21], Monostori [15] and Paelke and Röcker [22] have discussed some of the challenges associated with the design and implementation of CPPS. These are usually described in terms of increased technical complexity, the need for new interaction concepts that can consider the unpredictability of interaction between physical and the virtual worlds and the lack of prototyping and test tools. All of these challenges are relevant to HCI research and yet underexplored [23]. In particular, qualitative insights that explore contextual variation and the need for better tailoring of solutions are hard to find. In view of its relative novelty, this lack of research regarding CPPS is understandable. However, this is likely to change within the next 10 to 15 years, as investment in Industry 4.0 from national governments begins to kick in [24]. Together with the potential advantages of CPPS, e.g., enhanced productivity and flexible production systems [15, 22, 25], this trend underscores the timeliness and relevance of our own contribution.

2.2 The social nature of knowledge and its relevance in industrial contexts

Knowledge is a socially constructed and often distributed asset, whose management is deemed an important strategic resource for companies and a source of competitive advantages in the market [7, 8, 26–30]. In CSCW, the focus on issues of knowledge has been rather more on the sharing than on the management of such an asset. CSCW researchers have long since been investigating those issues under manifold designations, e.g., organisational memory, collective memory, collective intelligence, expertise location, etc. [7, 31] at least since the 1990s. All of these studies examine the role of information in organisational settings, concentrating on the social context and emphasising communication amongst knowledgeable workers in contexts like safety critical environments and office environments [7].

The HCI literature has also touched upon the matter, particularly with regard to the design of digital visualisation technologies for KES. Burkhard and Meier [32], for instance, address issues of sharing by introducing two theoretical concepts for knowledge visualisation, based on the use of visual metaphors and knowledge maps. The authors discuss how visual metaphors are powerful for KES but yet underused in organisations. Their results demonstrate the usefulness of visual metaphors in motivating people to engage in knowledge exchanges and in supporting learning processes. In particular, the authors found visual metaphors to support the presentation of new perspectives, increase remembering, enhance the focus and concentration of the viewer, and structure and coordinate communication. Many other studies followed Burkhard and Meier's. However, most of them have focused on teaching and learning [e.g., 33, 34] or issues of information overload [see for instance 35], rather than on KES within organisational contexts. In manufacturing contexts, even less material has been produced.

The assumption that the primary issue in relation to KES lies in making the previously tacit somehow more explicit has been challenged within the HCI and CSCW [3, 7, 36]. Research on the field has shifted the emphasis to the social, processual and other contextual factors which may influence KES. This, effectively, can be thought of as a specific element of the 'turn to practice' which characterises much CSCW work. This re-emphasis is particularly important when the potentially transferable skills under examination are 'embodied', relying as it were on a 'feel' for things [3, 37].

3 Methodology

In this section, we provide an overview of our overall methodological approach. We will not delve into details here, as these are given in sections 4 and 5 ahead. We will also address the limitations of our methodology in turn, so that the readers can judge its *trustworthiness* and *authenticity*, in assessing the quality of this research [38].

For our own purposes, we have drawn on Wulf et al. [10]'s DCS (Design Case Study) framework for GD [9]. GD is a solid and well-established design research paradigm, which puts focus on practices for the understanding of issues of design and the quality of designed artefacts. DCS, on the other hand, is a research design for this paradigm. Case studies, which have its origins in the social sciences, have been consistently used across different disciplines (e.g., psychology, sociology, HCI, and CSCW) to investigate and shed light on assorted types of phenomena [39]. DSC is built around this socio-scientific tradition and is, therefore, of highly scientific relevance.

The framework is mainly organised in three phases. The first phase sets out to understand user practices that can potentially be supported by technological solutions. The second phase, and actual design of the technology, comprises traditional user-centred and participatory design methods – see e.g., [13, 40] – to build a socio-technical system concept. The final phase encompasses a longitudinal study to investigate and document the deployment and appropriation of designed technological artefacts in the users' social systems. This article's contributions are based on activities of the first two phases of the DCS framework, namely *pre-study* and *design.* In particular, we focus on the results of the shadowing, eye-tracking, in-depth interview, document analysis, scenario-based design, DW (Design Workshop) activities and high fidelity prototyping activities. It is worth pointing out that the design phase was not constrained to scenario-based design, DW and high-fidelity prototyping; medium-fidelity prototyping, heuristic evaluation [41], cooperative evaluation and lab usability test were also involved in this phase, as seen in **Fig. 1**, although these are not addressed in this article – therefore they are greyed out.

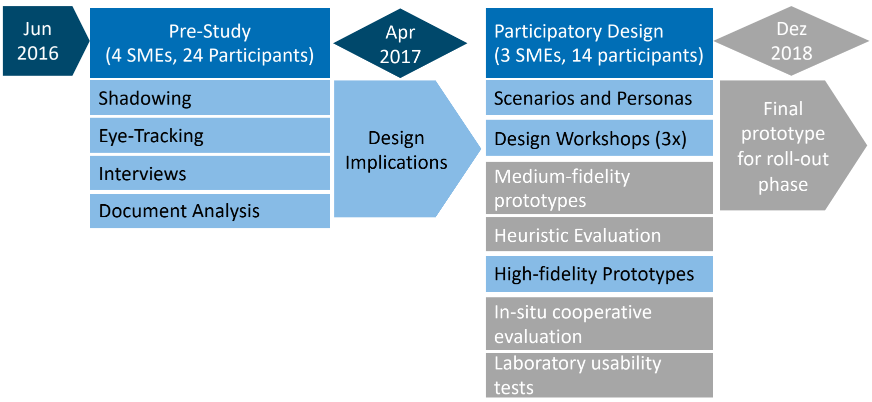

Fig. 1. Research Design Overview

Our pre-study consisted of an in-depth ethnographic study carried out over a period of 10 months (Jun 2016 – April 2017). By the end of this phase, we devised a series of initial design implication for AR-based CPPS to support machine operators with KES concerning context-specific industrial set-up, as seen in section 5. These design implications have been based on the machine operator practices and the challenges stemming from them, as introduced in section 4 below.

The identified design implications informed the design activities of the second phase, which started with a series of DWs, carried out between April and August 2017. These workshops have been carried out with representative users, therefore, observing the premises of PD (Participatory Design) approaches, which entails the involvement of the participants in the design decisions across all the design phase [40]. The results of the workshops fed into the prototyping activities, which resulted in the design concepts presented across section 5, as the design implications are discussed. The design phase activities extended until December 2018, as seen in **Fig. 1**.

4 Uncovering user needs concerning industrial set-up processes

In this section, we introduce our findings regarding machine operators' practices concerning industrial set-up and associated user needs stemming from it. These findings underpin the elaboration of a practice-centred model for industrial set-up as well as the design implications and envisaged solutions introduced across section 5.

The case we examine involves the set-up of machines used to bend material like metal tubes. In order to produce different products, these machines must be equipped with different tools. **Fig. 2** shows the rough flow of the process, which is described in more detail across section 4.1. Overall, the process starts with the machine being prepared for the process. This includes, for example, moving machine axes to certain set-up positions, so that parts can be removed and new ones can be installed. Subsequently, the necessary tools for the process must be found in the storage areas and organised in a desktop nearby the machine to be set up, therefore requiring certain logistics. The set-up process includes dismantling tools that were previously in the machine and assembling new ones for the manufacture of the new product. After the (dis)assembly operations, the production starts. As these machines are CNC (Computer Numerically Controlled), they must be configured through a variety of parameters. These parameters influence the efficiency and cost of the production by determining its cycle time and the quality of the product. An inspection establishes the quality and, if necessary, a new iteration cycle happens. For this purpose, the error pattern is viewed and the corresponding parameter is adjusted in the CNC code.

In order to understand the user needs regarding the process, we carried out a 10-month ethnographic study. Our study included investigations in 4 SMEs in 2 European countries. The main data collection instruments were: *shadowing,* for in situ data collection about the participants' work practices and the social system in which they unfold; *eye-tracking,* for detailed information about the steps involved in the process; and *in-depth semi-structured interviews,* to discuss design opportunities for a CPPS support and issues arising from the shadowing and eye-tracking data. Eye-tracking sessions were recorded with both the eye-tracker cameras and a stationary video camera, giving us micro and macro representations for post hoc analysis. The in-depth interviews were audio recorded and later transcribed. We performed a total of 14 shadowing sessions, with each session also featuring at least one eye-tracking session. Interactions observed before, during and after these sessions were documented through fieldnotes. A total of 24 in-depth interviews ranging from 45 to 120 minutes were performed.

Overall, 24 workers across the 4 SMEs participated in the study. Out of these, 7 were from company A; 13 from company B; 2 from company C; and 2 from company D. All companies are medium-sized and produce components for various customers. The age of the participants varied from 20 to 60. They occupied different roles in the companies, as for example foreman (n=5), production engineer (n=3), machine operator (n=9), process owner, etc. They also had different educational backgrounds, for instance, graduated unspecialised (n=2), graduated specialised (n=6), masters specialised (n=8) and job tenures (varying from 1 to 20 years of experience). This diverse group facilitates a better representation of the different stakeholders of the system [13].

We are aware that this is a relative small sample and that the findings of our study cannot be generalised. This is a widely acknowledged and accepted limitation of qualitative studies [39]. However, we have been careful to address issues of *trustworthiness* and *authenticity* [38] to assure the quality of our research. For that, we have used two strategies. First, we have used different data collection methods to allow for triangulation during the data analysis, i.e. cross-checking the consistency of the findings resulting from the data collected from these different methods [39]. Second, we have drawn on a systematic data analysis technique [42], to support us in the generation of the findings, as made clear below. The triangulation performed demonstrated consistency of the findings across the different data sources, reinforcing the trustworthiness and authenticity of the findings. This becomes visible when the findings coming from the pre-study interview presented in section 4 are corroborated by the ones coming from the DW in section 5.

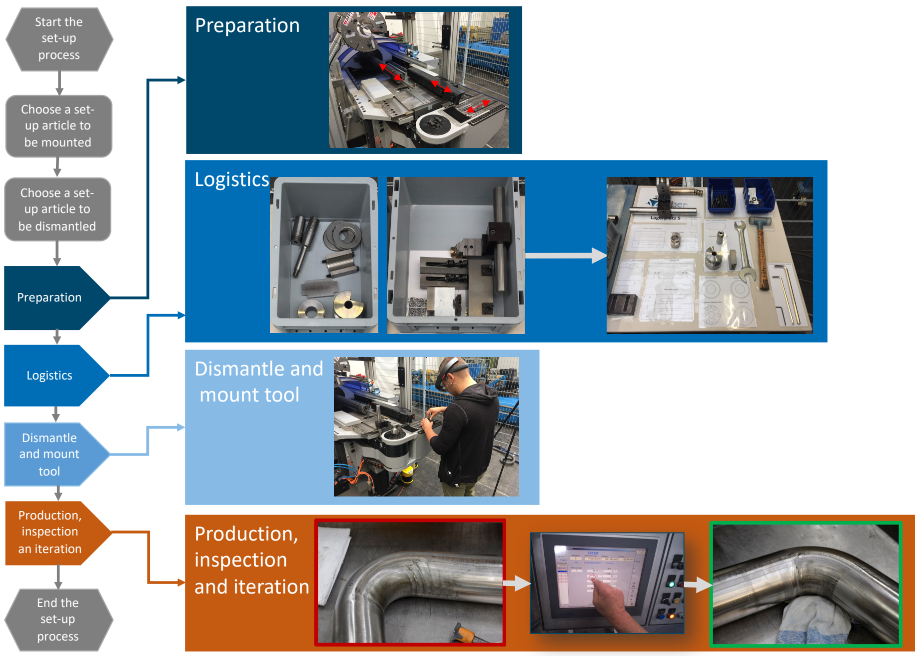

Fig. 2. Presentation of the general steps of a set-up process on a bending machine

The interview transcripts, fieldnotes and eye-tracking recordings were subjected to a TA (Thematic Analysis) according to Braun and Clarke approach [42], which entails a set of well-established steps involving open coding of the media excerpts, systematic revision of the coded segments and the identification of code-families and their relationships, to elaborate a deep understanding of the explored contexts and/or phenomenon. In relation to the eye-tracking material, we have gone through the videos recurrently, using the Tobii Pro Lab software and have also coded the relevant video excerpts. Information about the start and end time of the excerpt was recorded in a spreadsheet and assigned a referent code. Memos about the excerpt were also written to support posterior processing of the analysis.

The pre-study data sources were coded thoroughly. More than *70 codes* were identified and developed during this initial phase – e.g., *sequential execution of steps, expertise-based solutions, strategies to find answer to set-up problems.* These codes were further developed into themes, through careful analysis and characterisation of their relationships. *Four main themes* emerged from our analysis: (1) the workflow nature of industrial set-up; (2) the mixed relationship of dynamic and static elements with mechanic and non-mechanic operations; (3) the highly knowledge intensive character of the process; and the (4) potential challenges in interacting with any digital technology while working on it. We address each of these themes in turn in the next sub-sections and illustrate them with quotes from our participants. The quotes are associated with the participants who provided them. We refer to the participants through the notation *(participant number, job position, company, data source)*, where data source refers to the data collection instrument that originated the quote – i.e., interview, shadowing, eye-tracking or DW.

4.1 A workflow-like process

Our analysis of machine operators' practices concerning industrial set-up suggested that the process can be clustered in *6 interdependent* phases which resembles in many aspects a workflow. Based on the practices involved, we have named these phases as: *Preparation* (Phase 1), *Logistic* (Phase 2), *Tool and machine set-up* (Phase 3), *Production* (Phase 4), *Inspection* (Phase 5) and *Programme iteration* (Phase 6).

Workflows have been discussed in CSCW research as a sequence of subtasks in work processes that are carried out cooperatively. These subtasks are assigned to different workers, which contribute towards the accomplishment of a common goal. The route of the work is automatically defined as subtasks are completed and directed to the person responsible for the next subtask [43]. Like workflows, the industrial set-up can be split in several subtasks that will route the flow of work to the next subtask(s) upon their completion. Unlike workflows, these tasks are performed by the same worker and can happen in parallel with each other at times. This has important implications for the design of computer-aids to support it, as observable in section 5. In the following, we discuss and illustrate each of the industrial set-up phases that we have identified through the analysis of our empirical data.

Preparation phase. Our observations show that industrial set-up starts with preparation activities that specify the production process and are based on existing production resources, e.g., semi-finished products and machine and personnel availability. To efficiently carry out a set-up, machine operators need clear planning guidelines regarding the set-up to be carried out *"[...] so that you have a more rational and orderly set-up"* (P7, Operator, Comp. A, Interview). However, this is not always easily achieved:

> On the one hand, the stock must be minimised by making the production variable and carrying out many set-up operations. Conversely, it is important to keep the overall set-up times low by means of a small number of procedures. (P4, Production Engineer, Comp. A, Interview)

Hence, there is constant tension regarding how to respond to divergent production demands, which relates not only to the final product but also to the economics of production. We observed that participants would benefit from a working environment where there were fewer changes in production planning and therefore fewer interruptions. For the participants a lack of continuity is not just a disturbance, but is suboptimal. This results in time lost to both reconfiguring and restarting the process. Thus, the preparation phase includes a planning problem which should somehow be overcome, for example, by providing virtual process data to support planning decisions, as suggested in section 5.2.

Logistic phase. Parallel to all set-up phases, operators must deal with the logistics of the process, which refers mainly to bringing the tools and materials necessary to the set-up to the place where set-up will happen. Unsurprisingly, this is a critical step, which can potentially impact on the overall set-up time. If parts are not where they are expected to be, set-up time will increase [6, 44]. This is an issue concerning KES, as discussed in the design implication introduced in section 5.4.

Even the most experienced operators have problems with logistics from time to time. Analysis of the eye-tracking records showed that logistic activities can account for up to 21% of the set-up time. In the course of the observations we noted, in particular, that additional paths followed during the set-up contributed to disturbances in an ordered set-up sequence. For instance, the set-up of the same machine, with the same tools, for the same product, by machine operators with comparable experience varied from 63 to 97 minutes (mean = 79 minutes). Closer analysis of the eye-tracking data also showed that the routes leading to increased set-up times could have been avoided if a clear assessment of logistic activities had happened at the beginning of the process. These aspects informed the elaboration of the design implication presented in section 5.1.

Tool and machine set-up phase. In this phase, the necessary tools and machines components from the previous production order must be removed from the machine and the new ones should be assembled. Our observations showed that much of the set-up time was invested in this phase. Uncertainties here had a serious impact on the overall set-up time and it was not uncommon for workers to draw on the knowledge of their colleagues to solve particular problems. P5 (Operator, Comp. A, Interview), for instance says: *"If I cannot solve a problem, I can call at any time or use WhatsApp and then we do that in this way"*. Indeed, the relevance of experience-based knowledge for the tools and set-up phase was a strong feature of our fieldwork data from the outset. Although it has been acknowledged in the literature that set-up procedures are highly dependent on the skills of the workers on the shop floor [6, 45], so far this has not been appropriately explored. Our own data sheds light on this issue, drawing attention to the need for a system that can support seamless KES among workers, in particular those demanding particular know-how: "*Mounting the tools, every beginner with support would be able to do this. Changing values and parameters is, in turn, a matter of experience.*" (P7, Operator, Comp. A, Interview)

Hence, as the complexity of the mechanical activities increases, the know-how of the machine operators becomes decisive for a successful and efficient set-up. In principle, knowledge of the set-up process qualifies employees to perform these activities without further restrictions. As discussed in the next section, this raises relevant issues of KES, which are addressed in the design implication discussed in section 5.4.

Overall, our findings suggest a need for instructions that generally represent the steps concerning the tool or machine set-up in question. This tool *"should actually have a representation of how the tool should be mounted on the machine"* (P6, Operator, Comp. A, Interview), so as to ensure that the set-up runs smoothly. This also relates to the implications in sections 5.2 and 5.3.

Production, Inspection and programme iteration phase. These three remaining phases have been found to be seamlessly interleaved and, therefore, are presented together here. Overall, our analysis suggests that the Production phase – when the artefacts are really manufactured – does not present any special challenges with regard to time or content concerning set-up. The Inspection phase – where optical tests and tactile measurement are carried out in a test run component – did reveal some issues, however. In the course of the actual set-up, the verification of component quality plays a special role because the results of any tests have direct implications for the set-up itself and the subsequent programme iteration phase. *"If the part is not true to gauge, I must intervene in the process and change machine parameters."* (P1, Foreman, Comp. A, Interview).

Bending processes generally provide for a gauge test by the operator. The key thing about gauge tests is that geometrical deviations are directly recognised and converted into changes to the machine programming. This programme iteration phase can be described as success-critical. It is characterised by intensive parameter adjustments on the man–machine interface (MMI) as deviations in the manufactured product are spotted. These aspects connect directly with the design implications presented in sections 5.1 and 5.2, as will become observable.

4.2 Static and yet dynamic

Another relevant finding from our analysis is that industrial set-up involves both a static and a dynamic dimension, which have certain relationships with mechanical and non-mechanical set-up operations performed during it. **Fig. 3** introduces a model that we have elaborated out of the practices that we have observed in this regard. This model is organised into four abstracted areas of activity, concerning characteristics relating to the documentability and explicability of the set-up operations we have observed.

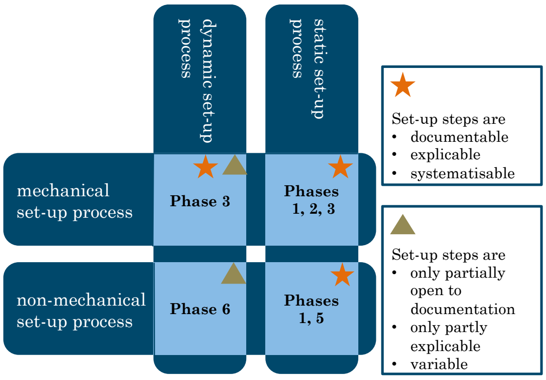

Fig. 3. Practice-based model for industrial set-up

From our perspective, this model represents a relevant advancement in the understanding of industrial set-up. Existing models, like the SMED model proposed by Shingo [6], depicts a twofold process consisting of external and internal set-up operations, our findings suggest this is a limited way of seeing industrial set-up. Our findings suggest that set-up is far more complex than it has been depicted to date. Our model therefore provides a more nuanced treatment of the practices relating to set-up.

In principle, our findings showed that it is possible to distinguish between relatively constant, or repetitive, set-up operations (static) and highly variable set-up operations (dynamic). For instance, some of the findings previously introduced demonstrate how industrial set-up refers to a rational and orderly process, which can be carefully planned. During our triangulation activities, the eye-tracking and the observation data of the logical activities showed that the *Logistics* phase also displays characteristics of static operations, since tools and other components required for the set-up must be placed at defined locations in order to allow easy access and quick handling. The *Tool and machine set-up* phase also involves some static operations, for example dismantling tool and machine components, although some of the operations from this phase would better fit the dynamic aspect of the process.

With regard to the mechanical and non-mechanical characteristics of the process, our findings suggest that the mechanical part of the set-up includes mounting and disassembly, whereas the non-mechanical part contains interactions with the user interface of the machine – e.g., configuring the CNC code. As a matter of example, the *Preparation, Logistic* and *Tool and machine set-up* phases are characterised by mechanical operations, within which the machine operator has to do physical work to complete the set-up process. The *Preparation* and *Inspection* phases have some operations which do not involve any mechanical interaction.

In terms of the characteristics of the steps involved in industrial set-up, our findings suggest that some of them are documentable. In other words, there are steps within the set-up process that can be easily documented by virtue of their simple and quick explicability. In Nonaka et al.'s [46] words, these steps can be easily made explicit. From our own observations, these steps are also easily 'systematisable', for instance, by the use of checklists, as suggested by the SMED approach [6].

Despite the fact that many set-up steps are explicable, documentable and systematisable, *many of them are not*, either because the machine operators cannot always articulate the reasons for their actions or because the underlying set-up actions display high variability, as illustrated by previous findings. This is particularly the case with non-mechanical operations and mechanical operations related to the dynamic dimension of our model. An example of the former are manual adjustments of the machine programme and, of the latter, adjustment of the position of a tool on the machine axis. These issues have implications, as discussed in the section 5.5.

4.3 Highly dependent on knowledge

The findings presented so far suggest that industrial set-up is a knowledge intensive process. The high proportion of knowledge intensive operations gives KES a decisive role here. Our analysis revealed a strong need to initiate KES among colleagues because expert knowledge lies within a very restricted cohort. Moreover, as contingencies arise in this context, the knowledge needed is held by relatively few [31, 47]:

> [...], 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, Production Engineer, Comp. A , Interview)

This is particularly relevant for new employees, who often lack experience. However, the knowledge in question is both extensive and diverse, so conventional KES [7, 31, 48] is especially challenging:

> Even if everything has been shown [to you], you have to make your own experiences. There are many tricks that you do not immediately master. It is incredibly extensive what can happen there. These are many things that cannot be passed on. You can manage a large amount, but everything will never be passed on. (P5, Operator, Comp. A , Interview)

Furthermore, personal transmission of experience can become burdensome: *"Over time, that is exhausting. I had to explain every step what he should do."* (P14, Operator, Comp. B, Interview). There are two issues that contribute to this. First, as visible before, there is a systematic lack of documentation. Another is that the existing documentation is usually very abstract and often outdated. As a result, the existing documentation generally ends up not being used. Sharing knowledge and expertise emerged as a success-critical basis for allocation of resources – see implication for design in section 5.2. If an effective system for KES were in place, *"I would not sit here and I would be released [to be working on something else]"* (P5, see earlier, Interview).

Nevertheless, such a system is not easy to devise. In general, various information formats are considered helpful: *"Visual and written information and also a video"* (P6, Operator, Comp. A, Interview). The persistence of embodied knowledge emerges as an important requirement for the tool: "*If you get help from the experienced co-workers, they make the changes and explain, but in the end, you look only and then you forget at some point"* (P6, see earlier, Interview). This relates directly to the fact that experience-based knowledge is mostly of the embodied kind [3]. In other words, much of the understanding of how to handle particular parts of the process only becomes visible when it is observed in action. This is difficult to convey [29, 48]. Such difficulties call for innovative ways to record and visualise this type of knowledge. CPPS, it has been claimed, is about to result in a revolution in the way that knowledge and expertise can be shared, by providing ways to conveniently capture and display knowledge embodied in action [3], without the need to translate this knowledge into propositional knowledge, the driving approach in industrial and organisational management [46], as discussed in the design implication introduced in section 5.1.

4.4 Interaction challenges in industrial contexts

Set-up processes take place in real production environment contexts. Requirements for the design and development of a system support to help machine operators, need to take into account the realities of these kinds of physical environments. For instance, both our observations and interviews stressed the fact that operators must have *"both hands*" (P10, Operator, Comp. B, Interview) available to carry out set-up work. Moreover, we have observed that the workspace where industrial set-up unfolds is very limited, *"due to the large number of tools and tools combined with limited storage space, we always have a problem with space"* (P5, Operator, Comp. A, Interview). Last but not least, *"dirt and noise"* (P10, see earlier, Interview) must also be taken into consideration. One the one hand, the system must be sturdy enough to take on eventual accidents without breaking: *"You need to have something you can work with. If it falls off, don't break it"* (P11, Operator, Comp. B, Interview). Conversely, the environmental noise must not interfere on its functioning or in the interaction with it, as observed in our fieldwork, meaning that voice commands, at least in the current stage of the art, would be an unfeasible mechanism to interact with the envisioned technology. These aspects have informed the elaboration of the design implication discussed in section 5.6.

5 Designing CPPS to support industrial set-up

As previously mentioned, the findings from our pre-study led to the identification of a series of design implications for the design of CPPS to assist machine operators with industrial set-up. These implications had mainly to do with the six identified phases of the set-up process that have been elaborated out of the understanding of the machine operator practices concerning the process. We brought these implications to the attention of our fieldwork participants in a series of DWs, discussing with participants the extent to what the identified implications would correspond to their needs and expectations. In these workshops, potential technologies that could be used to address those requirements have also been discussed. The results from these activities have ultimately led to the design solutions that we introduce and thoroughly discuss in the course of this section.

In total, 3 DWs have been carried out – 1 with participants from Comp. A, 1 with participants from company B and, 1 with participants from Comp. C. Identified requirements have been introduced to participants by means of scenarios and personas, following a scenario-based approach to design [49]. DWs lasted from 4 to 8 hours. Around 6 participants were involved in each of them. Most participants in the DWs had also participated in the pre-study, and therefore could confirm or disconfirm our interpretation of the data. DWs have been audio recorded. The audios have been transcribed and also submitted to TA, as the pre-study data, i.e., code categories have been identified and revised and the relationship between those categories have been explored elaborated and formalised in themes [42].

In summary, *6 themes* have been identified in terms of implications for design, namely: (1) use of sensors to collect real data; (2) use of digital simulations in situations there is no real data available; (3) support for aggregation digital data to work practices; (4) support for KES; (5) support for data configuration; (6) provision of feasible interaction in industrial contexts. These themes are not only based on the data analysis of the DW data, but also on the pre-study data.

Interestingly enough, the identified themes resonated to a large extent to with Lee et al.'s 5-level architecture for the design of CPS, introduced in our related work section [20]. Nevertheless, our findings extend Lee et. al's architecture, as Lee et. al's architecture concentrates solely on the technical aspects and does not engage with the socio-technical aspects of the design and the affordance of creating an environment in which KES processes can take place. The following sub-section details how these 6 design implications can extend Lee et al.'s 5-level architecture for the design of CPS and what they meant for our design decisions [20].

5.1 Use sensors to collect real set-up process data for subsequent use

Our findings suggest that contextual information relevant to the process is something that can be captured, combined and prepared using a CPPS that draws on human practices or technical sensor technology. This somehow relates to Lee et al.'s smart connected level of CPPS [20]. Appropriate sensor technology could be implemented through different identification systems, like barcodes or RFID systems [50] and connected to the CPPS. In so doing, the system would be able to support machine operators with operations from phases 1 and 2 introduced before:

> The Holo-Lens would be connected via the W-LAN. That means I can access everything that is available via W-LAN, i.e., if we have such a reader for an RFID chip that we can access via the network. (P23, Comp. B, DW2)

This design implication led to a series of design decisions for the AR-based CPPS elaborated during the participatory activities carried out during the design phase of our DCS. **Fig. 4** illustrate how this have been implemented in practice.

In summary, for logistic activities, sensor technologies have been employed. Sensor technologies can play an important role in recording paths and providing data for subsequent optimisation (see **Fig. 4** [b]). As evident in the quote below, this sort of tracking would be a relevant aid in optimising the time used for the set-up process:

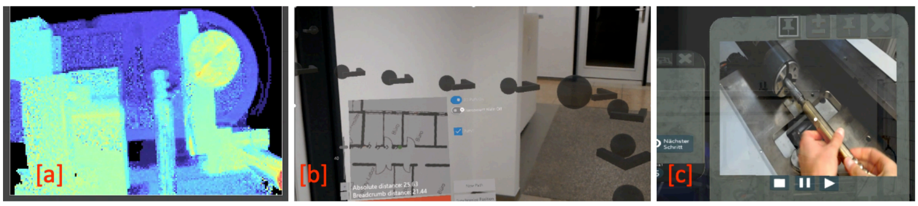

Fig. 4. First level: Sensory check of the size and position of the mounted tools [a], the recording of the set-up paths [b] and the video recording of the set-up interaction [c]

> From the methodological point of view this is a typical SMED procedure […] (T)here is a so-called spaghetti diagram where the paths covered by setter during this set-up process are shown. (P25, Comp. B, DW2)

In addition to that, machine operators can be assisted in unambiguously identifying the tools as well as in determining their position on the machine axis by selecting the tools through sensor-based recognition (see **Fig. 4** [a]). Not only that, by means of sensor technology, local knowledge embodied in action can potentially be recorded in videos and shared (see **Fig. 4** [c]). In other words, sensor technology has the potential to show product-specific characteristics to workers in real time, enabling context-sensitive dispositions, so to avoid wasting time and other resources in the accomplishment of the set-up process.

Real machine data can also be beneficial if individual values can be assigned to a quality image of the article. This speaks directly to user needs that were captured in phases 5 and 6. Furthermore, there is a need to share knowledge about the machine settings that could be used for different situations, i.e., the knowledge about the different parameters that can be defined for each tool axis, which describe the geometry of the article to be manufactured and the procedural. Capturing and sharing this knowledge in a contextualised way can offer a significant added value for other operators in the course of the dynamic set-up process.

5.2 Provide virtual process data to support decisions in situations where real process data is not available

The results we have presented across this article implies that CPPS should not only be consisted of real data, but should also be enriched with virtual data, as for example, by blending 3D holograms with the real machines as demonstrated in **Fig. 5** [a], or by providing simulation data as seen in **Fig. 5** [b]. This resonates with Lee et al.'s *Conversion* level of CPPS architecture, which suggests that CPPS should generate smart analytics for machine component health, multidimensional data correlation and degradation and performance prediction. Phase 3 introduces requirements for a virtual confirmation of the assembly process.

In this case, a virtual construction environment can potentially circumscribe this activity [51, 52]. Separately, the assembly process must be free of collisions. This can be ensured through virtual kinematic simulations in the preparation phase and with the help of AR visualisations on the real machine during the set-up process (**Fig. 5** [a]). In addition to that, phase 6 presents an even more complex requirement for virtual data

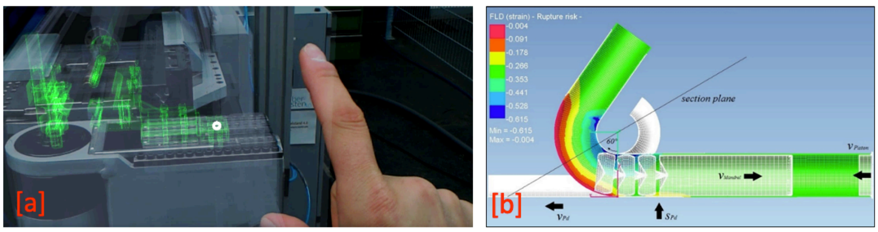

Fig. 5. Second level: The recording of the virtual set-up interaction [a], the generation of virtual process data by means of an FEM simulation [b]

concerning the configuration of the machine parameters. Hence, virtual production data, which considers the material reactions of the semi-finished products in detail, can offer some added value, because the settings can be derived in advance of the real set-up process. At the same time, the need for specific settings can be clarified by means of material stress parameters (**Fig. 5** [b]). Here an operator can interpret the colour coding of the places with the highest stress and introducing specific countermeasures, locating the exact position of maximum load and tracing it back to a tool movement with the aid of the diagram.

The virtual generation of process data, then, can allow for the translation of certain aspects of local knowledge into propositional content, to be used during the performance of actual mechanical processes. This virtual data can potentially complement the real data generated by the use of sensors.

5.3 Supporting human-centred aggregation of data

From our results, it is relevant to support a human-centred aggregation of data, or in other words the aggregation of experience-based knowledge 'owned' by workers. Put differently, data has to provide an added value for KES:

> If I first use this system to create a kind of story book for the set-up process, to link individual data to a manual and then afterwards have the possibility to move or change this data again in a different order in my office, then from my point of view I have all the possibilities I need to create a knowledge base. (P25, see earlier, DW2)

However, this is limited by the capacity of people to recall all of the specific details [8, 53]. For instance, the demands from phases 1 and 2 represent the need for data aggregation in the form of (primarily) master data about an article and its associated tools. The master data serves as a cornerstone of an article to be produced. Likewise, they form the foundation for their digital representation [54]. This resonates with the third level of Lee et al.'s architecture for CPPS, which has to to do with a *Cyber* level where twin models for components and machines are generated and managed. The twin model is a virtual representation of the real machine and describes the behavior of the machine in the virtual world.

Our results also indicate that a set-up operation can benefit from a digital representation of the haptic aspects of the process (see **Fig. 3** 'static set-up process') as well as essential data for the machine's adjustment (see **Fig. 3** 'dynamic set-up process').

> If I have the 6 different positions in front of me [where I can assembly a tool] in the machine, the HoloLens must show me the position with a virtual representation of the tools. In addition, information about the assembly is stored in a window above the machine. All information must be directly visible when looking at the machine, but must not obscure the assembly location. (P31, Comp. C, DW3)

Fig. 6 [a] and [b] show the implementation. The data recorded on the lower two levels are assigned to a set-up step and saved afterwards. The virtual data is stored in an AR animation of the set-up interaction and machine data is visualised on a dashboard. However, the data only adds value for a learning-friendly environment if it is aggregated realistically and is situationally relevant, detailed and problem-oriented [20]. Furthermore, the data must come directly from the production process. A reduction of complexity can be achieved: by a) ensuring the provision of the data takes place in a context-sensitive fashion and b) that it is directed to support key elements of decision-making [19]. The aggregation of real and virtual data and their representation in embodied action and through propositional knowledge correlate strongly with the mechanical and non-mechanical as well as the static and dynamic set-up components.

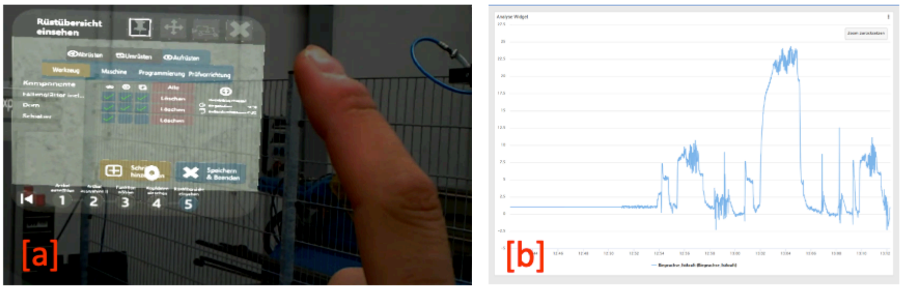

Fig. 6. Third level: The storage of the recorded set-up data in the HoloLens [a], the visualisation of the machine data [b]

5.4 Support knowledge and expertise sharing (KES)

Integrated simulation, connected systems, remote visualisation for human and collaborative diagnostic and decision making are some issues addressed by the fourth level of Lee et al.'s [20] CPS architecture, namely *Cognition* level. Not surprisingly, the long-term storage of knowledge and the individual and independent accessibility of multimedia content is an important advantage in an industrial environment [30, 55–57]. This has been extensively discussed within the CSCW and HCI literature, which has been investigating OM (Organisational Memory) and KES issues since the early 1990s [7].

As discussed across section 4, some critical operations of the set-up process are intensively influenced by experience-based knowledge. Nevertheless, we have observed that written documentation is fragmentary, not up-to-date and does not capture the necessary level of detail:

> I think it would be cool if we could manage to get the mediation that you can say, I get for the respective tools that I want to install now, with which torque they theoretically have to be tightened and which screws, for example, or all of which must be used for this tool. That I really only have to grab my belt and I have everything I need. I also know with which pretension. (P23, see earlier, DW2)

Advanced systems have significant potential to support the contextuality information [22]. De Carvalho et al [3] introduces a discussion about how CPPS can support KES by allowing new ways to convey information embedded in embodied action. We have further pursued the authors' initial ideas and have made it concrete in the technological aid that we put together to support machine operators in carrying out machine set-up. **Fig. 7**

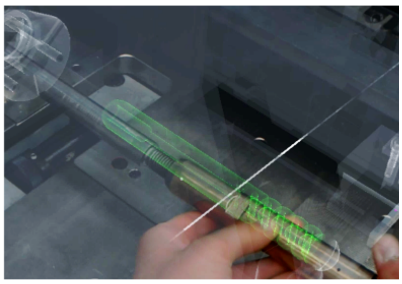

Fig. 7. Fourth level: The replay of the recorded set-up data

shows the visualisation of the set-up interaction, which was recorded on the second level of the CPS architecture and now is aggregated on the fourth level to a complete set-up instruction, using an AR visualisation. On the basis of this interactive instruction, set-up information is available independently of people's availability and a KES can take place on the basis of the recorded and visualised set-up information.

5.5 Support knowledge and data configuration

The findings concerning the phase 1 stress the importance of standardised processes and therefore the need to provide interactive checklists according to well-defined and clear foundations in order to avoid failures. During the DWs, it was made clear that for supporting machine operators with their daily set-up activities, the system has to be able to access databases that contain logistic real-time information with regard to the name, storage location and condition of the respective target object:

> So, there are databases for certain things and links for certain things, so I know which tools are necessary for this article […] it would make sense for our set-up editor to continue thinking in databases, i.e., we create a complex tool database. (P7, Operator, Comp. A, DW1)

In a second step, users can potentially interact with the system by confirming or verifying physical availability as well as the target state of the target object. Moreover, by such means, users can be guided step-by-step through the working task and receive multimedia support in terms of texts, pictures and videos [58]:

> If I can see a 3D model, then that is certainly not bad. Additionally, it can be enhanced with pictures and videos. With this data a standard set-up instruction can be created […] probably not perfect yet […] Because at the beginning the experience knowledge is not there yet, it is only built up with time. (P33, Comp. C, DW3)

The observations above resonates with the fifth Lee et al.'s [20] architecture for CPPS, namely *Configuration* level. Iterative approaches where machine operators evaluate a best practice, then modify accompanying processes such as logistic tasks, influence the actual set-up tasks. Although, some mechanical set-up operations are static, it is possible that there will be an impact on the handling processes as well. Existing set-up instructions need to offer adaption options for these changes.

This implication resonates with the realisation that frameworks, which actively support learning processes of the worker, must adapt to innovations and changes [5]. Overall, then, any support system will need to meet these requirements. In particular, changes in set-up order need to be developed cooperatively and, if appropriate, through actual interaction. For this purpose, a tablet client, which can adjust the aggregated set-up data by changing the sequence of the set-up steps, was implemented (see **Fig. 8**).

5.6 Provide feasible interaction mechanisms for the manufacturing context

A final implication for design that we have identified concerns a vertical level that permeates all other 5 levels of Lee et al.' [20] architecture: it concerns the interaction challenges faced in the everyday life activities of machine operators. These challenges mainly emerge from the interactions between users and the system in the environment where the system is deployed:

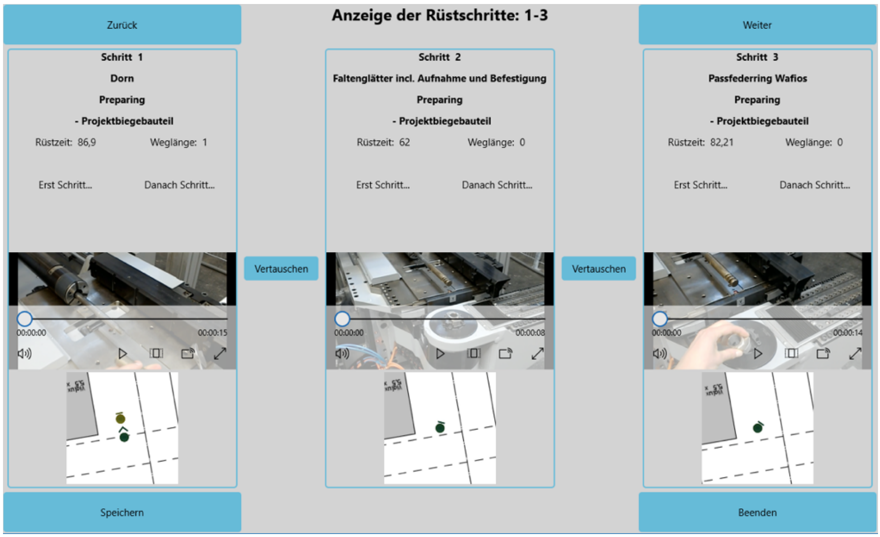

Fig. 8. Fifth level: Adaptation of the set-up process

> […] weight of the glasses, […] the wearing comfort [should be] there. The recording quality of the videos has to be good, that you don't have to focus so exactly on the window, but that you can move freely. The same with the sound quality. When I record something, I want to make sure that it is of the appropriate quality, that the background noise is not so present and that you can understand what the colleague is saying […] (P30, Comp. C, DW3)

In more detail, these challenges encompass: 1) allowing the machine operator to operate hands-free; 2) local, mobile and decentralised access to information because of the manual reconfiguration processes which are performed directly at the machine; 3) recognising the limited working space around the machine. Therefore, the central ergonomic design aspects of the CPPS should be oriented to the principle that the interaction of the machine operator will not be affected negatively during the whole process. The aim is not to achieve the simplest possible interaction, but rather to sensitively adapt the complexity to the field of application [59]. Moreover, the support system should support shift work, which is pervasive in industrial settings. Thus, the CPPS needs to facilitate communication regarding KES between the separate steps, firstly, to offset temporal variability, and secondly, to provide teaching and training material. These requirements cannot be limited to specific phases, but they are essential for all phases of the set-up process. For the reasons listed here, we decided to use AR-visualisation with the help of Microsoft HoloLens. The set-up instructions, as described above, are recorded and also played back with the HoloLens. In addition, the HoloLens serves as a sensor for recording the set-up paths. The main advantage of using the HoloLens is the gesture-based interaction and the visibility of the set-up information – independent of the position of the set-up person – spatially adapted to the real machine.

6 Conclusion

This article introduces a series of timely and relevant contributions to the HCI research. Timely because they refer to the design of CPSS, a type of system that has been receiving increasingly attention of the community and the market, but has not yet been fully explored in the HCI literature, especially because only recently it has been proposed as a solid concept to be explored in design [15, 60]; relevant, because they address a context not yet widely explored in HCI (manufacturing contexts) and introduce findings shedding light on how these systems should be designed, in order to be useful and usable and to fit to users practices. These three last aspects are key for system acceptability and appropriation, as discussed extensively in the literature [10].

In answering our first research question, we have demonstrated that industrial set-up is a knowledge intensive process involving an ecology of practices that make it really challenging. Our findings certainly overlap with other CSCW studies on KES, as for instance the case of sharing knowledge about technical questions in organisations [31, 47] or about medical diagnosis and care activities in medical settings [61, 62]. Nevertheless, our findings point towards a case of knowledge concentrated in the hands – or the heads, if one will – of very few actors, where the 'social distribution of expertise' is of a highly concentrated kind. Different from Bardram and Bossen [61], who discuss how medical and care knowledge was distributed across different actors and its implication for mobility work, our case reports on a small number of experienced machine operators that hold important knowledge concerning the set-up of the varied machines. The manufacturing context explored also has its particularities, as demonstrated by our findings, as has the addressed process, i.e., industrial set-up. All those elements sum to the novelty of our contribution. Furthermore, our implications for CPPS, which have not yet been extensively explored for KES [3], provide us with opportunities to advance the state of the art.

In terms of our second research question, our findings suggest that CPPS should be able to capture and support both the static and dynamic dimensions of set-up, ultimately leading to more effective KES by the machine operators. The use of sensors can potentially support operators in capturing different set-up scenarios that can then be learnt from down the line. Furthermore, the subdivision into processual knowledge which is represented by embodied action, as well as the presence of propositional knowledge can be reflected in the representation. While the static and mechanical set-up process is primarily characterized by embodied action components, the dynamic and non-mechanical set-up process is characterized by propositional knowledge components. Furthermore, as discussed by de Carvalho et al. [3], CPPS can support effective KES by providing new ways to capture, process and visualize relevant knowledge that can potentially trigger improvements in the process.

All in all, the findings regarding manufacturing contexts (e.g., re. noise in the environment) can potentially be transferred to other similar contexts (e.g., construction contexts). The same applies for the findings concerning processes which are workflow like and demand the use of both hands to be accomplished. The observations and the solutions herein presented can, we argue, inspire other design solutions or even sparkle new HCI research.

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