Human Interventions in the Smart Factory – A Case Study on Co-Designing Mobile and Wearable Monitoring Systems with Manufacturing Staff

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ABSTRACT

So-called smart factories with networked physical machinery and highly automated manufacturing processes offer huge potential for efficiency and productivity increases. While respective user-centered research has been investigating assistance solutions for concrete maintenance or assembly tasks, this paper explores worker-oriented mobile and wearable systems for monitoring such complex and demanding manufacturing environments and for preparing for potential interventions. In four co-design workshops and focus groups, we investigated a manufacturing staff's requirements for such monitoring systems and designed and evaluated low- and high-fidelity prototypes. Based on these insights, we derive a set of general design recommendations for mobile and wearable monitoring systems for smart factories.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile devices**; **HCI design and evaluation methods**.

KEYWORDS

smart factory, worker, monitoring, intervention, co-design

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1 INTRODUCTION

Summarized under the term *Industry 4.0*, the increasing digitization and automation in the manufacturing domain through connected physical machinery and the analysis of large amounts of data promise higher levels of operational efficiency and productivity [13, 17]. While originally driven from a technology perspective (data formats, connectivity, interoperability, etc.), research on the so-called *smart factory* and corresponding *smart manufacturing* processes increasingly address human-related aspects such as changing roles of manufacturing staff (cf. [12]) and their transition towards "strategic decision-makers and flexible problemsolvers" [7].

Most of the relevant prior research and existing solutions can be classified into two groups: First, extensive visualization approaches for monitoring smart factories through operators and managers at office workplaces (cf. [25]). Second, mobile and wearable assistance applications for supporting workers in concrete tasks (e.g., maintenance, assembly), often using head-mounted displays (HMD) and augmented reality (AR) approaches (cf. [10]). In contrast, worker-oriented research on overseeing large amounts of networked machinery on the shop floor, unobtrusively monitoring the production state, and preparing for interventions is scarce.

To tackle this gap from the workers' perspective, we investigated their requirements for mobile and wearable monitoring systems in four co-design workshops and focus groups involving low- and high-fidelity prototypes. The contribution of this work is twofold: First, we introduce our successful methodological approach for co-designing with production staff. Second, we present a set of general design recommendations for worker-oriented monitoring solutions derived from the workshop insights. The respective results are relevant for both practitioners and researchers in the field of human-centered assistance solutions for smart manufacturing.

2 RELATED WORK

This section briefly reviews relevant research pertaining to (1) user experience of wearable and mobile industrial assistive devices and (2) co-design processes in industrial contexts.

(a) Co-design workshops with sketching tasks.

(b) Focus groups involving functional app prototypes with real-time notifications.

Figure 1: In co-design workshops (a) and focus groups (b), prototypes of mobile and wearable monitoring systems were designed and discussed with manufacturing staff.

2.1 UX of Industrial Assistive Devices

The usage and interaction with industrial wearable and mobile devices fundamentally differs from large-size screens and monitors [14], which are predominantly used in this context [25]. Therefore, the evaluation of mobile and wearable systems in the industrial context is important and early work dates back to the 1990s. For instance, Siegel and Bauer [19] conducted usability tests and derived functional requirements for a wearable system consisting of touchscreen, dial, and HMD in the avionics sector. More recently, in the context of Industry 4.0, Kong et al. [9] propose multiple design considerations (e.g., ergonomics and data interaction) for industrial wearable systems based on a survey.

Wearable and mobile AR tools, especially HMDs, have lately received particular attention. Specifically, Jetter et al. [8] utilize a mobile AR tool for automotive maintenance and evaluate its perceived usefulness through questionnaires. Similarly, Siew et al. [20] also examine industrial maintenance tasks, but include haptic feedback through a wrist-worn device. Regarding HMDs, researchers (e.g., [21] and [22]) have run field studies using AR-HMDs and collected users' self-reports to highlight their usefulness. Funk et al. [5] compared different modalities (haptic, auditory, visual) for providing error feedback for manual assembly tasks.

Other works assessed the use of industrial wearables by conducting field studies and employing questionnaires or guided interviews. Specifically, Aromaa et al. [1] evaluate a wearable system combining smartwatch, smartphone, and AR glasses through the System Usability Scale (SUS) and Papp et al. [16] conduct guided interviews after field testing an exoskeleton. While these studies mainly focus on general user experience and user acceptance, research on user-friendly information presentation or visualization remains scarce. Some generic design recommendations arise from the Intervention User Interfaces paradigm [18], which fits naturally within the setting of Industry 4.0, but remains to be empirically validated. Mach et al. [14] present more specific findings related to smartwatches by suggesting to display single items instead of longer item lists. While their lab-based setting included non-industrial tasks and untrained participants, similar conclusions regarding the displayed information are drawn elsewhere [24].

In spite of these efforts, further research is needed to investigate best-practices and design recommendations for user-friendly wearable and mobile interfaces in smart factory environments.

2.2 Co-Design in Industrial Contexts

Context plays an important role in user experience [11], which is why some researchers focus on incorporating worker knowledge through co-design processes in order to design useful tools for industrial assistance. For example, Buchner et al. [3, 4] create UX prototypes for a specific factory environment by leveraging participatory workshops with maintenance personal. Along similar lines, Osswald et al. [15] create wearable prototypes for the same industrial setting through experience prototyping, thereby taking the work context of industrial employees into close consideration. Zenker and Hobert [24] utilize workshops next to qualitative interviews for eliciting requirements and evaluating their smartwatch-based industrial assistance system.

Moreover, some research solely addresses the context of user experience in industrial settings, without subsequent application of a specific wearable or mobile technology (e.g., see Wurhofer et al. [23] for an overview in the semiconductor fabrication). More generally, however, only little consideration has been given to context and co-design processes that could make industrial assistive systems more useful [2].

3 METHOD

This section describes our methodological approach for involving factory workers in the design and evaluation of a wearable and mobile monitoring system. The research was conducted in cooperation with *Geberit*, a globally active manufacturer of sanitary products. Geberit employs about 12'000 people worldwide and has highly automated state-of-the-art production facilities.

Figure 2: One example of the iterative co-creation of a wearable monitoring app from sketches (left) over wireframes (middle) to a functional prototype for a Wear OS-powered smartwatch (right).

3.1 Requirements Workshops

To gain an overall understanding of the work context and its requirements as well as to co-design suitable solutions with the actual users, we conducted two requirements workshops (Figure 1(a)) with six and five production employees, respectively. In each workshop, a project manager and a quality manager provided additional remarks and insights into relevant requirements and tasks of the manufacturing process from a management perspective.

The workshops were conducted by two researchers. One acted as the main moderator, the second supported in moderation and documented participants' statements. Each workshop comprised three phases: following an overall introduction, the second phase discussed intervention scenarios and corresponding information requirements, and the third phase addressed suitable devices (smartphone, tablet, smartwatch, data glasses) for the work context. During the workshops, app sketches were created in a co-design approach (Figure 2, left). As materials, we prepared low-fidelity wireframes (several variants for mobile and wearable devices as a starting point for discussion), photo-realistic mockups (to convey experience of wearing a smartwatch with a respective app), and templates for sketching tasks. Each of the workshops took about two hours.

3.2 Prototyping

After the two requirements workshops, the collaboratively designed wireframes were converted to more formal mockups by the involved researchers (Figure 2, middle). In a further design iteration, these mockups were discussed with the involved managers to eliminate potential misunderstandings. Eventually, based on the finalized mockups, functional prototypes in form of a *Wear OS* app (Figure 2, right) and a progressive Web app (using *Angular*) were created. The resulting stand-alone apps could be directly executed on Wifi-enabled smartwatches and smartphones. Through a custom simulator software, predefined example error and warning messages could be sent to both apps via *Firebase* for demonstration purposes.

3.3 Focus Groups

In two focus groups, we confronted six production employees with the functional prototypes (Figure 1(b)). Three smartwatches with the prototypical app installed as well as three smartphones with the respective Web app were distributed among the participants. Again, the project manager and the quality manager were present for providing a management view. The two researchers who had also run the co-design workshops conducted a scenario-based walk-through. Scenarios such as picking up the devices at start of work, selecting machines, receiving incident notifications, and resolving incidents were visualized through presentation slides while the participants experienced the corresponding app states in functional prototypes.

4 WORKSHOP RESULTS

Overall, the participants highly appreciated a mobile/wearable monitoring solution for receiving notifications about machine-related incidents. While machines are equipped with status lights that indicate malfunctions or warnings, not all machines are constantly operated or monitored by a worker, especially during focused work on another machine. Furthermore, the lights are not visible from all sides and production sites can be extensive.

4.1 Information Requirements

In this section, we summarize the participants' statements with regard to their information requirements. During the qualitative analysis, the statements were coded and grouped topic-wise.

Incident Presentation. From the two examples provided by the researchers as inspiration (a simple overview of the machines' states vs. a more detailed map-like presentation), the participants favored the more compact presentation form. They argued for an abstract stripped-down presentation focusing on relevant incident information. Only one participant recognized advantages of the latter presentation for either very extensive production lines (e.g., spanning two floors) or for novice workers not entirely familiar with their working environment. In general, the participants emphasized their preference for incident-based notifications over real-time visualizations.

Notification Content. The participants proposed notifications with very limited content. One example mentioned was *"Machine 4, cell 1, cable damaged"*, i.e. machine name, location, and a compact error/warning description as the crucial content parts. According to the involved workers, any further details about the incident are visible at the machine display and thus do not need to be included in a notification.

Notification Prioritization. All workshop participants emphasized the necessity of prioritizing multiple notifications active at the same time, in particular, for devices with limited display size such as a smartwatch. They favored an automated ordering over a manual one, while pointing out that the priority of messages (and the pivotal machines, respectively) might change according to the currently active commission. If errors occur at two pivotal machines at the same time, the staff currently approaches the shift supervisor which machine to fix first. A smart automated prioritization of messages could save this communication and increase reaction times significantly.

Notification Recipients. In an extensive production environment comprising dozens of machines, like in our case study, each member of the production staff has the responsibility for certain (up to 8) machines. As the participants pointed out, these responsibilities differ among production lines: In one production line they are defined for a period of one week, in another one machines are newly assigned each morning by the shift manager, and in a further one the workers agree on a suitable allocation themselves spontaneously. Each production worker knows his/her responsibilities, yet these assignments often are not explicitly written down. To avoid any distractions during their work tasks, the participants demanded a mechanism to only receive messages for the machines they are currently responsible for.

Notification Categories. Regarding the current incident categories of most of the machines, the participants agreed on two main types of notifications: errors (critical for production, requiring an immediate intervention) and warnings (non-critical information, e.g., about upcoming events without the need of an immediate action). According to the participants, the errors to be communicated via a mobile or wearable solution should directly correspond to the respective errors defined through the machine. However, while at the machine's display follow-up errors may be visible, the participants proposed to not send out notifications about such additional errors: *"Important for us is the initial error message; the consequent errors are resolved as soon as we have fixed the first error."* Example messages for warnings include notifications about reaching a specified target number of items, an upcoming change of commission or article (*"New commission at machine 5 in 10 minutes!"*), a (upcoming) shortage of material (*"Filling level at machine 3 below threshold!"*), and an upcoming (regular) inspection of a machine. Currently, such information is communicated either by shift managers or visible at the machine. Furthermore, they proposed to reuse the existing color codes (red for an error, blue for a warning) within the monitoring app to support the quick comprehension of a message's severity.

Incident Resolution. Once a worker resolves an incident, potential other workers who are also responsible for the respective machine need to be informed about the intervention. Thus, a monitoring app needs to provide an opportunity to confirm the resolution of an incident and to make the respective notification disappear for other recipients of the notification. The involved quality manager suggested that, after an incident is marked as fixed, the worker should be able to select the cause of the incident and the measures for resolving it. Currently, this information is collected only infrequently (written down manually). Capturing it through a mobile or wearable device could significantly increase both quantity and quality of the data set and this knowledge base could be used for creating recommendations on suitable measures in future.

Further Notifications and Services. During the workshops, the participants came up with several ideas for additional notifications and services for the envisioned communication system. For example, two participants described the delivery of new material from a warehouse to the production site where the responsible staff is notified about its arrival through an automated phone call. The participants considered a respective notification on a mobile or wearable device more convenient. Regarding the notifications about machine failures, the participants proposed a feature for forwarding the notification to a maintenance technician in case they are not able to fix the error themselves. Furthermore, the participants proposed a generic messaging function for shift managers to distribute miscellaneous work-related information to their team or specific team members. In addition, they discussed advantages for the staff to take a shift manager's phone call via a wearable device such as the smartwatch. Two additional features mentioned for the envisioned system were the opportunity to take and forward photos of a machine's state and to visualize the current location of team members within the production site in case a face-to-face discussion is urgently required.

4.2 Suitable Devices

From the four device types (smartphone, tablet, smartwatch, data glasses) introduced, the participants clearly preferred the smartwatch and the smartphone. The smartwatch received the most positive feedback and was considered *"least disturbing"* during the staff's work while still being able to receive and display messages. Some participants had concerns regarding clarity and legibility if multiple messages were active at the same time and suggested a smartphone for these cases. However, they emphasized that this must not be one more device additional to a company cell phone or private device, yet rather replace an existing one. Consequently, device functionality currently used for work must be available on new devices as well. As an example, three participants emphasized the importance of a time display, i.e. if a smartwatch-based solution is rolled out and workers take off their private wrist watches, a smartwatch app should constantly display the current time. One participant mentioned the combination of a smartwatch app for convenient notifications with a smartphone app presenting incident details. Three participants discussed employees' varying requirements and recommended different devices per role: While workers might use a smartwatch with push notifications for errors and warnings, a shift supervisor might additionally use a smartphone for accessing the manufacturing resource planning tool.

Due to the high mobility of the staff, a typically-sized tablet was considered *"cumbersome to carry around all the time"* and thus less suitable for work purposes. In case a larger screen is advantageous, the tablet still *"should fit into the pockets"* of their work suits. Otherwise, two participants feared, the tablet might be placed at a machine and forgotten in the factory. For the envisioned use case of continuously monitoring and unobtrusively notifying about the production state, data glasses were disliked by all participants. While the participants discussed potential usage for specific setup and maintenance tasks, they were found bulky and uncomfortable to wear during an entire 8 hours shift.

A crucial requirement mentioned by all participants was the robustness of the devices. The participants described their daily manual activities (such as reaching into machines during repair or setup tasks), which require rugged hardware. To avoid damages, private wristwatches are taken off for such tasks in many cases. Two participants described their good experiences with screen protectors and recommended similar protections for the smartwatches.

Finally, the participants favored individual devices over shared ones and agreed that each production worker should have his/her own device. Explanations given multiple times included hygienic reasons as well as a certain commitment to take good care of the devices. Furthermore, participants discussed about a central place for storing and charging the devices and considered the workplace where shift meetings take place suitable.

5 PROTOTYPE FEEDBACK

This section summarizes insights from two focus groups involving functional prototypes of a smartwatch and a smartphone app identical in functionality. Overall, the participants' feedback for both the wearable and the mobile prototype were positive without any critical complaints about their usability.

5.1 Proposed Usability Improvements

The apps' main view showed the machines the app currently receives incident notifications for. While for testing and demonstrating purposes a limited number of machines could be selected within the apps, in production a worker can be responsible for up to 10 machines and the names of all machines should be visible, as two participants pointed out.

At the same time, they suggested larger font sizes for several screens, in particular when discussing the wearable prototype, to improve legibility during work tasks or in stressful situations. For both displaying more information and improving legibility, the participants identified screen parts which could behave adaptively. In the wearable prototype, the company logo, current time, and the user's name might shrink or even disappear as soon as more space for displaying machines' names and notifications is required.

The color-coding of the messages, based on the common color codes of the existing machines, ensured the participants' quick recognition of the severity of the message categories. Furthermore, vibrations for incoming messages (with different patterns for errors and warnings) were considered highly valuable by all participants to raise a worker's attention in noisy environments.

Furthermore, the participants recommended to further shorten the length of vertical selection lists in the wearable app (e.g., for subscribing to machines' messages or selecting the reason of a failure and the corresponding measure). For facilitating machine selection, the participants proposed to use hierarchical menus, i.e. first selecting a group of machines, then choosing individual machines from this submenu. For shortening the causes of failure and the worker's potential measures, the items may be grouped and only the currently suitable ones be presented (e.g., for specific machines and specific failures only a subset of causes is applicable).

5.2 Proposed Additional Features

While experiencing the functional prototypes in a live demonstration during the focus groups, the participants found additional useful features not yet integrated. Five of them requested a "pause" function for the app to silence messages during their breaks. Four participants proposed color-coding the selected machines to highlight the machines which are pivotal for the current production and thus, require particular attention.

Further services envisioned for the wearable and mobile apps during the focus groups included detail views for machines with information beyond current errors and warnings such as upcoming maintenance dates. In order to improve the information flow between workers during shift handovers, two participants proposed to make a list of errors and warnings, which had occurred during the prior shift, available on the succeeding worker's device.

6 DESIGN RECOMMENDATIONS

Based on the insights into workers' requirements, we derived a preliminary set of design recommendations for wearable and mobile monitoring systems geared to production staff in highly automated manufacturing environments.

Provide compact notifications. The content of notifications regarding machine incidents should be reduced to a minimum: Information about the severity (two categories: errors and warnings), the machine's name (and rough location), and a very short description of the incident are sufficient for a worker to prepare for a corresponding intervention (e.g., scheduling the intervention, selecting tools) and proceed to the machine. Detailed information is available directly at the respective machine's built-in display.

Design for demanding work contexts. While testing app designs in situations that involve user movement is a general design guideline for apps (cf. [6]), the demanding work contexts in manufacturing environments require particular consideration. Examples include stressful situations that require workers' quick reactions, possibly during movement in poorly lit factory areas. Thus, interaction and navigation, particularly on wearable devices, must be simple, intuitive, and error-tolerant. Clarity and legibility must be optimized through using larger font sizes and high contrasts.

Offer multimodal feedback. For further support, mobile and wearable monitoring apps should make use of multimodal feedback beyond purely graphical presentations. In particular, vibrational alerts for incoming notifications are highly valuable for drawing busy workers' attention during work tasks in noisy environments. Different vibrational patterns should be used to indicate the severity of incidents.

Reuse familiar designs. Experienced workers are familiar with the incident presentations available at specific machines. A monitoring solution for workers should reuse existing designs and patterns to facilitate the recognition of prior situations. One example is reusing color codes for machine groups or incident categories.

Manage notifications smartly. Since workers might be responsible for multiple machines, they need to be supported in keeping track of several currently active messages – which is particularly challenging on wearable devices with limited screen size. Thus, the monitoring system needs to manage notifications smartly by prioritizing messages (on incident categories, crucial machines, etc.), enabling forwarding of incidents to fellow workers, or silencing notifications during breaks.

Support flexible machine assignments. Since machines can be assigned to workers in different ways (e.g., daily changing, constant for one week), even within one company, a monitoring solution for workers should support both predefined (by the shift manager) and self-defined (by the worker) machine assignments. The machines currently subscribed by the device user should be displayed in the monitoring app, for noticing a faulty configuration easier and foster trust in the system.

Choose robust lightweight devices. For unobtrusive monitoring solutions for manufacturing staff, lightweight wearable devices are preferable over devices with larger screens. Crucial functionality are real-time notifications, whereas detailed visual presentations do not provide additional value for experienced workers. Smartwatches are favored over data glasses and suffice for communicating most relevant incident information. Devices need to be protected considering workers' manual tasks such as maintenance activities.

Capture workers' knowledge. When designing monitoring systems for manufacturing staff, collecting additional work-related data (such as workers' knowledge and contextual information) in respective apps should be considered. These data can provide the basis for further process optimization and prospective digital services in the factory. An example is prompting for the cause of a machine failure and the worker's measure for in-depth maintenance analysis and recommendation algorithms.

7 CONCLUSION AND OUTLOOK

In this paper, we presented our human-centered research on mobile and wearable monitoring systems for manufacturing staff. In two co-design workshops, the factory workers discussed requirements of such solutions and drafted wireframes of potential apps. After multiple design iterations, these were realized as functional prototypes and evaluated by production staff within focus groups. Based on the overall insights into the requirements of such systems, we compiled a preliminary set of design recommendations for such applications. In our future work, we will evaluate the functional prototypes in a field study under real-world conditions to validate and extend our current design recommendations and to study the apps' impact on relevant industrial performance indicators.

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