Designing a Mobile Communicator: Combining Ethnography and Object-Oriented Design

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ABSTRACT
Communication and coordination of mobile and distributed work activities is a challenging application domain for mobile handheld devices. In this paper, we present the design of a mobile system to support communication and coordination between workers in safety-critical tasks in a power plant. The design of the system was based on ideas inherited from a communicator that was developed for a different application domain. The design was devised through a combination of ethnography and object-orientation. The mobile system we designed provides location-aware access to computerized information and process control on a handheld wireless computer terminal.

Author Keywords
Ethnography, Object-Oriented Design, Handheld Devices, Mobile Computing, Field Evaluation

ACM Classification Keywords
H5.2. [**Information interfaces and presentation (e.g., HCI)**]: User Interfaces - *User-centered design, Graphical user interfaces, Screen design*

INTRODUCTION
Many industrial work settings require workers to be highly mobile and physically distributed while at the same time relying heavily on centralized computer-based information and process control systems remote from their current location, and of careful coordination of work activities. Research has shown that in such settings, increased value can be gained from the use of mobile and networked computer systems. Examples count remotely controlled service robots for the elderly or disabled (Hüttenrauch and Norman, 2001), wastewater treatment process control (Nielsen and Søndergaard, 2000), early diagnosing in emergency ambulances (van den Anker and Lichtweld, 2000) and coordination of distributed work activities on board large container vessels (Kjeldskov and Stage, 2006). Designing mobile computer systems for industrial domains is, however, not trivial. Work activities involve high risks in the case of errors, and erroneous actions may cause serious material damage and possible injuries on personnel or loss of human life. Thus, careful studies, analysis and evaluations have to be performed.

Some of the central activities in interaction design projects are to determine what modalities to use, what content and functionality to present at what time, how to organize and layout content on the screen, and making sure to use mappings and metaphors that are understood by the target users. The literature on mobile user interface design provides many examples of specific solutions where designers have carefully considered these challenges. However, the way these designs were conceived and the relation to underlying, often ethnographically based, analysis of the use domain is rarely described in a methodical manner enabling others to learn from the process (Kjeldskov and Graham, 2003).

In this paper, we describe how we designed a mobile handheld communicator to support the coordination of distributed collaborative work tasks at a large industrial power plant. Specifically, we emphasize how we reused the basic design idea of a communicator for a different but comparable application domain, and describe how data from an ethnographic field study was processed using an object-oriented design method and how the relevance of our design was assessed through a series of prototype iterations on different levels of fidelity. In the following section we describe our background in terms of the design ideas we inherited from a communicator for a different domain. Then we present how we designed the communicator for our domain. We describe the final prototype that was evaluated in the field and the results of this evaluation. Finally we provide the conclusion.

BACKGROUND
Our design process was inspired by a published study of mobile computerized support to communication and coordination in a safety-critical domain. That study involved detailed inquiries into communication on board

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large Maersk Line container vessels. The outcome of the study included design and evaluation of a maritime communicator; a handheld device to support communication and coordination on the container vessels. The literature from this study describes the basic design ideas as well as the design and evaluation processes (Kjeldskov and Stage, 2006).

Figure 1. The user interface of the maritime communicator.

The user interface design of the maritime communicator integrates physical location, language, role and task. The interface does that by combining the following elements into a coherent overview (see Figure 1):

- The current status of the overall task (graphical image at the top)
- A history list of completed tasks (first list)
- A list of on-going tasks (second list)
- A list of possible orders (scroll list at the bottom)

The basic idea was to replace spoken communication with exchange of text messages, similar to SMS or chat applications. The key advantage of this was that the communication became persistent. The messages were predefined which made the issue of a command a matter of selecting the relevant message. The list of possible orders depends on the role of the user.

The design of the maritime communicator was based on an ethnographical study of communication on board the container vessel. This study identified a number of shortcomings in the use of spoken communication transmitted through handheld VHF radios. The design idea was to overcome these by means of text-based communication on mobile devices. The text messages were predefined and they came out of the ethnographic study.

OUR DESIGN PROCESS

Our design process was carried out in collaboration with Nordjyllandsværket (see Figure 2), a large coal-based power plant situated on the outskirts of Aalborg that produces central heating and electricity to Northern Jutland.

The collaboration with Nordjyllandsværket allowed us to try out the design idea embodied in the maritime communicator for container vessels (see previous section) and the methodological approach used to develop it, but in a different application domain.

Our design process involved two major activities:

- Ethnographic field study
- Object-oriented design

Based on this design, we implemented a functional prototype and evaluated it in the field. The ethnographic field studies were carried out in September and October 2003. Object-oriented and design was conducted in October and November 2003, and implementation of the functional prototype was done in November 2003. Evaluations were conducted in the field in collaboration with workers at Nordjyllandsværket in December 2003. The content and outcome of these activities are described below.

Figure 2. Nordjyllandsværket.

Ethnographic Field Study

Ethnographic field studies in the work domain were a significant basis for designing the maritime communicator. We decided to take the same approach with the power plant project. We wanted to gather rich empirical data about the use domain before engaging in design, which required spending long periods of time in the field.

We wanted to focus our field studies on a limited part of the power plant. It was suggested by stakeholders at the power plant that we studied work activities at the fuel department, as the operation of this part of the plant is essential for ensuring a continuous production of energy. Also, this department involves workers distributed over a large physical area relying on centralized computerized controls and careful coordination currently based on spoken interpersonal communication in a particularly noisy environment. The machinery makes it a safety-critical domain.

The field study consisted of a series of visits to the fuel department of the power plant interviewing the workers and observing their work areas and tasks. This took place over a period of two months. The visits were documented with photographs of work places and artifacts, and through video recordings of the way key tasks were carried out. This provided an understanding of the application domain and insight into the communication problems characterizing the work. Communication was based on wireless phones and VHF radios. These devices are problematic because of the very noisy environment.

Below, we provide an overview of the work activities at fuel department, and of the nature of the problems with communication and coordination that are experienced by workers during their daily work.

Work Activities at the Fuel Department

Work activities at the fuel department are particularly safety-critical because of the machinery involved and the danger of fires breaking out. Tasks are carried out in collaboration among several workers who must be able to continuously communicate with each other, even if they are not located in the same place. As a central part of the work in the fuel department, workers survey the production line, continuously monitor the running of machinery, and carry out maintenance and repairs.

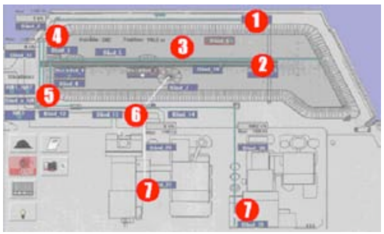


Figure 3. Overview of Nordjyllandsværket indicating key work locations of the fuel department.

The power plant (see Figure 3) is divided into two separate production plants (locations #7). The fuel for the two plants is supplied from a large central coal storage area (locations #2 and #3). The fuel-department is responsible for delivering the coal used in the two production plants, amounting daily to 5000 tons of coal for each. The employees in the fuel department continuously monitor and control the transportation of coal and must ensure that the correct amount of coal arrives to the correct location, and that the coal has certain properties and quality. In order to ensure this, the coal is filtered and grinded (locations #4 and #5). After the coal is processed, it is transported to the two production plants (locations #7) by means of underground conveyer belts (see Figure 4).

Figure 4. Underground conveyer belt transporting coal.

Another important task for the workers in the fuel department is to prevent the coal from self-combusting in the storage area.

Communication to Support Coordination

The workers perform a variety of different tasks to ensure that the amount of coal that is needed is delivered to the two production plants. In order to coordinate the many tasks described above, quick and easy communication is important, and in some cases even essential, in order to carry out the job in a safe and efficient manner. At present, communication is done via VHF radios, DECT wireless phones, and some times mobile phones.

Currently, the control tower (location #6, see Figure 5) is the only place where all necessary information is accessible. It is also the place where employees can operate and control most of the machinery.

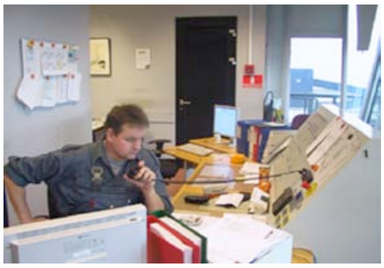


Figure 5. The control tower.

The overall operation of the coal transport can be controlled by means of the existing computerized process control system. However, when a problem occurs, which cannot be solved from the control room, for example in the Grinder building (location #5), the personnel sent to the site to solve the problem do not have direct access to the control system. Conversely, the specific parts of the individual machinery distributed throughout the plant (for example physical handles on the Grinder) can only be operated on site. Hence, full control of the plant requires communication and coordination between personnel on site and in the control room.

Communication Problems

Even though DECT phones, VHF radios, and mobile phones (see Figure 6) are used a lot because of their flexibility and portability, several problems were reported and observed in relation to their use.

Figure 6. Worker talking to the control tower through a mobile phone.

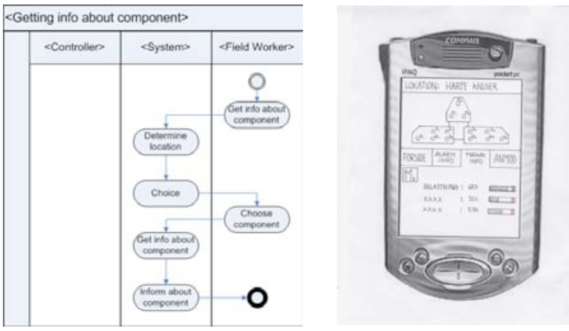
Firstly, since the conveyor belts run underground and many machines are located inside solid concrete buildings, radio communication is not always reliable due to lack of signal strength. Secondly, there is typically a deafening noise in the tunnels under the plants and inside the buildings, which makes talking to each other difficult and the use of any kind of mobile device for verbal communication virtually impossible. In summary, the workers experience communication problems related to three issues. One is lost signal, the second is noise, and the third is lack of information access.

Object-Oriented Design

In order to process our field data systematically and make them usable for design, we adopted techniques from two object-oriented methods, OOA&D (Mathiassen et al., 2000) and Wisdom (Nunes and Cunha, 2001a, 2001b). Similar techniques were employed in the design of the maritime communicator (Kjeldskov and Stage 2006). The combination of OOA&D and Wisdom has been described in methodological form (Nielsen et al., 2006). The detailed design of the user interface was based on the Bridge method (Dayton et al., 1998).

Initial Analysis

We described the system context of the Mobile Power Plant Communicator in an early class diagram that captured the most central objects in the context of a mobile system for the fuel department workers. We also did user profiling in order to describe more detailed the workers whose work activities should be supported by the system. The outcome of this was the identification of the two primary roles of *controller* and *field worker*.



(a) (b)

Figure 7. Outcomes from the first design activities: (a) an essential task model for getting information about a component (a machine or a part of a machine) and (b) the corresponding user interface of the first paper prototype

Modeling essential tasks turned out to be a bit more difficult because many tasks at the power plant were only carried out rarely, and not all of them happened during our field study. In order to overcome this problem, we decided to stage a series of situations in which the workers *acted-out* (Howard et al., 2002) work activities, communication and coordination in real world settings, allowing us to observe these rare, but relevant, situations. On the basis of our ethnographic observations and observing workers acting-out, we identified nine essential tasks that should be supported by the system. For each of these tasks, an activity diagram capturing the flow of the task was produced (see Figure 7(a)).

First Paper Prototype

To validate our understanding of the work domain and the outcome of the initial analysis, we created a non-functional paper prototype (Snyder, 2003) consisting of a series of screens drawn on paper, with functionality simulated by manually changing which drawing was placed on top of a PDA (see Figure 7(b)).

This paper prototype was evaluated with real users on site at the power plant, enabling us to get an overall idea of the applicability such a system. The evaluation consisted of a series of informal sessions at the fuel department, where different workers acted-out their use of the prototype, leading to discussions about required functionality and the prototype's structural design. The evaluation also resulted in modifications of the essential task models, and yielded a number of useful new design ideas.

Object-Oriented Analysis

Following the field study, initial data analysis and evaluation of the first paper prototype, we conducted a full object-oriented analysis (cf. Mathiassen et al., 2000). The aim was to refine the structure of the system and to support design and implementation by identifying classes, events, behaviors, and functions. The basis for these activities was the data from the ethnographic field study. Thus the object-oriented techniques were used to formalize the field data. The class diagram included 9 classes, and the list of functions in the system counted 22 functions.

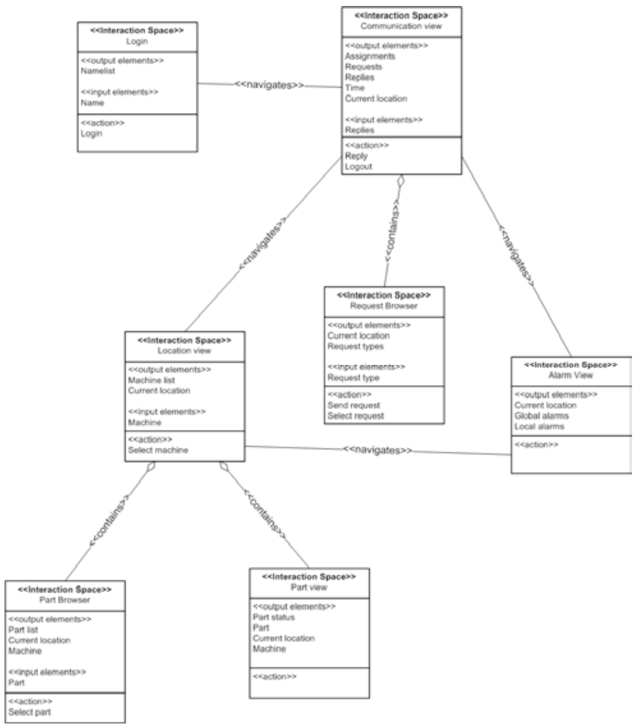


Figure 8. The presentation model for the system.

Object-Oriented Design

After the object-oriented analysis, we began designing the basic structure and user interface of the Mobile Power Plant Communicator. We started our design work on an abstract level by developing two related models of the interface on different levels of abstraction: a *presentation model* (Figure 8) and a *dialogue model* (Figure 9). The presentation model describes every screen of the system:

what each individual screen should contain in terms of output elements, input elements and possible user actions.

The attributes of the presentation model classes are defined on the basis of the class diagram for the problem domain. The operations are defined by distributing the function list developed earlier on the individual presentation model classes.

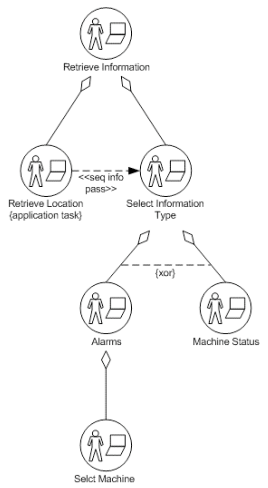


Figure 9. Subset of the dialogue model: getting information about a machine, corresponding to the task in Figure 7(a)

The dialogue model is a collection of diagrams describing user interaction when carrying out a specific task using the system. The dialogue model describes sequences of system use by decomposing tasks into interrelated sub-tasks. Thus, this model gave us an overview of how the workers would typically use and combine the different parts of the system allowing us design for these particular sequences and combinations.

Figure 10. Mapping of presentation model classes to concrete user interface design

User interface design

The user interface design departed from the design ideas of the Maritime Communicator. We wanted to provide information about the location and task and to enable the user to issue requests and commands from a list of predefined choices.

The first step of the detailed user interface design was to transform the presentation and dialogue models into concrete user interface design in the form of a second non-functional paper prototype. While not providing any detailed information about exactly what the user interface should look like in terms of, for example, the specific look and grouping of interface elements, the presentation model *did* provide a detailed list of elements that we had to include on each specific screen, and the dialogue model described the sequence by which the workers would typically interact with the screens.

As illustrated in Figure 10, knowing what information and functionality to provide when, proved to be highly valuable information in order to maximize the use of the small screen real estate of the target platform (Dayton et al., 1998). In order to reduce complexity, Figure 10 only depict some of the connections between interaction spaces and screen design.

Second Paper Prototype

As a final activity in design, a second paper prototype was made and evaluated with prospective users while acting-out a series of realistic scenarios in situ at the power plant. Following the evaluation, the user interface was further refined.

FUNCTIONAL PROTOTYPE

We implemented a functional prototype that met the requirements and realized the user interface design of the second paper prototype. The implementation activity amounted to a total of 20 person-days, which was mostly spent on implementing the necessary code for robust network communication. Below, we describe this prototype.

Hardware and Architecture

The Mobile Power Plant Communicator was designed to run on iPAQ 3630 handheld computers (or newer) running Microsoft Pocket PC 2002 (or newer) and connected through a wireless network.

Due to the harsh conditions of the use domain, in which pen-based interaction might be problematic, we decided to facilitate finger-based interaction on the touch screen and the use of the device's 5-way key. In addition to the handheld terminals, a desktop PC interface was designed for use in the control tower. The desktop PC application works as a server containing a formalized representation of the power plant and typical work activities. The handheld terminals log on to this server and identify their physical location, following which an appropriate interface is displayed on them. During use, function calls and commands are exchanged over the network, using handshake to confirm delivery, thus eliminating commands being "lost in the air". All network traffic is broadcast but processed and represented differently on each device in accordance to their physical location. As an example of general context-awareness, requests are automatically sent to the central computer to turn on the light when the user is entering a building.

The Mobile Power Plant Communicator was implemented in C# using Microsoft Visual Studio .Net 2003 Professional and the .Net Compact Framework. The prototype consists of approximately 3000 lines of code, which is largely dedicated to interface design and functionality.

Interface Design

The Mobile Power Plant Communicator provides distributed workers with access to information in the central computer system about the general status of the plant and about the specific machinery within their proximity. It also gives them a simple and flexible text-based communication channel for coordinating certain work activities. The system is divided into three overall screens with a number of associated sub-screens:

- Communication screen
- Alarm screen
- Status screen

These screens can be accessed through panes at the bottom of the screen. At the top of the screen, the system indicates who is logged in, where the user is located and what time it is. This information is important for the field workers because it gives them a frame of reference for interpreting the information and functionality provided by the system. Time is important because all communication, alarms, and actions are time stamped.

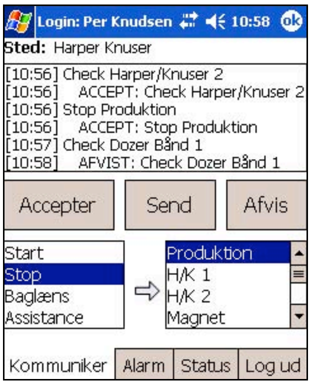


Figure 11. The communication screen.

The communication screen

The communication screen (Figure 11) provides workers with a text-based communication channel, that was inspired by the Maritime Communicator. It consists of 1) a field displaying the ongoing conversation, 2) two lists for composing a new message, and 3) buttons to send a new message or make a standard reply.

At the bottom of the screen, the user can compose a message by combining a list of verbs and a list of nouns (for example “stop production”). The lists of nouns and verbs were derived from the field studies and analysis and can be easily extended in the case of new work activities or machinery.

Above the two lists, there are three buttons for accepting, sending or rejecting a request. To avoid pressing the wrong button by mistake, the buttons for accepting or rejecting are placed furthest apart. Above the three buttons, the ongoing conversation is displayed on a list. The list is divided into a series of conversation threads, grouping communication about the same object or task together. To make a clear difference between requests and confirmations, the latter are indented and have their first word (for example ACCEPT or REJECT) in capital letters. In order to add a new message to a specific thread of communication, the user select the specific utterance on the list (for example “ACCEPT: stop production”) that he or she wants to reply to.

The reason for dividing the pre-defined messages into two lists was a difference from the Maritime Communicator. We had a large number of locations, and similar requests could be issued at each of these. Thus the users often needed more flexibility than provided by simple standard phrases, and that a complete list of all combinations would be too cumbersome to browse. Because the system knows where the workers are physically located at the power plant, it can deduce which machinery they are most likely to be communicating about (generating the list of nouns). Knowing about the functionality of the machinery, the system can deduce what actions the user can request (generating the list of verbs).

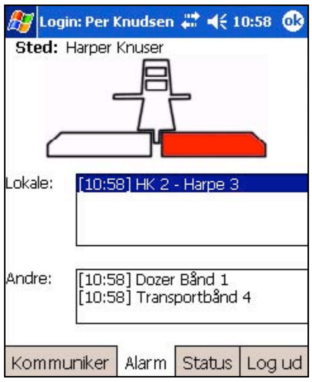


Figure 12. The alarm screen.

The alarm screen

The alarm screen (Figure 12) alerts the distributed workers if something is wrong at the power plant and provides them with the available details about the problem. If an alarm is associated with the users location, detailed information is displayed immediately. The alarm screen contains a graphical representation of the machinery in question, with the area of the problem highlighted in red. This is done in order to provide a simple visual index to the physical environment and to provide the field workers with a clear indication of the origin of the problem.

Below the graphical representation, there are two lists displaying alarms at the users current location and other alarms along the production line. These lists were included because the occurrence of a problem along the production line often causes other problems to happen, requiring co-located workers to start coordinating a shared strategy. Using these lists, the workers can get an overview of the cause and/or effects of a specific problem, thus assisting them in assessing its criticality. In addition to the textual description, each alarm also has a timestamp, which enables the workers to determine their sequence and current relevance.

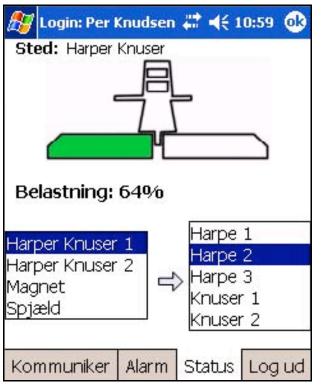


Figure 13. The status screen, corresponding to Figure 7(b)

The status screen

The status screen (Figure 13) provides workers with access to information about machinery in the production line within their close physical proximity (such as the load on each component). Furthermore, the screen can function as a remote control to some machines basic operations such as start, stop and reverse commands.

The status screen looks similar to the alarm screen in many ways. At the top of the screen, there is a graphical representation of the machine being accessed, with the specific part chosen being highlighted. If the chosen part of the machine is functioning or the load on the part is at a normal level, it is highlighted in green. If the load climbs towards a critical level, the color changes to orange. If reaching a critical level, the color changes to red and an alarm is activated.

Below the graphical representation, the users can choose which of the machines within proximity they want to work with (the list on the left), and what specific part of it they want to access information about (the list on the right). If there are no machines within proximity of the user, the status screen is not available.

Figure 14. Field evaluation of the Mobile Power Plant Communicator

FIELD EVALUATION

The prototype was evaluated in the field in collaboration with workers at the power plant (see Figure 14). Five workers aged 42 to 55 years participated in the evaluation. They had all worked at the power plant for several years, most of them for more than 20 years.

As in the evaluation of the two paper prototypes, the workers used the system for a series of real work activities that are typical for a normal working day while more uncommon work activities were acted-out in situ. One researcher managed the evaluation and asked questions for clarification. Another researcher recorded the evaluation on a handheld video camera shifting between focusing on the workers, the settings, and the screen on the handheld device (figures 13 and 14).

Figure 15. Close-up of the communicator during field evaluation.

Due to the noise level in some buildings, thinking-aloud did not always work well. In these situations, a post-interview was conducted outside the building immediately after.

The overall results of the evaluation showed us that the system was indeed usable and that the workers were happy about using it and were looking forward to a full implementation. The users had no problems understanding and adopting the basic functioning of the system. Some compared it to sending SMS messages on their mobile phone. Others compared it to a remote control. In relation to the communication screen, the users reported that they liked to be able to combine text-based messages and spoken communication over the VHF radio. Text-based communication was primarily found useful when noise prevented spoken commands but was also reported very useful in complex situations where they otherwise needed to remember what had been said when and by whom.

Regarding the alarm screen, the users reported that the annotated graphical representation would help them greatly in locating and fixing a problem quickly. In relation to this, some reported that they would like even more detailed graphics and preferably a plant overview as well.

Regarding the status screen, the users found the simple access to information about and control of machinery within close physical proximity compelling and highly useful for their daily operation of the plant. Adapting information and functionality to the users' location was also found to be easy to use and limiting the time spent on operating the system. Furthermore, not being able to operate machinery out of proximity was perceived as a significant safety advantage.

Regarding physical interaction, the users generally didn't like to use the 5-way key, but were very happy to interact with the touch screen using their fingers rather than a stylus – even when wearing gloves. On the negative side, the evaluation also revealed 14 usability problems experienced by the users on different levels of severity to be addressed in the next iteration of design.

CONCLUSION

We have presented how we designed a Mobile Power Plant Communicator. This was accomplished by combining ethnography and object-orientation for the design and implementation of a functional prototype. The ethnographic field studies allowed us to get a rich insight into the work activities at the power plant, informing quick design of a first paper prototype. Evaluating this paper prototype with prospective users in situ was used as a vehicle for validating and extending this understanding. The object-oriented design allowed us to structure data from the ethnographic field study in a way that supported both user interface and technical system design on a high level of abstraction. The models and diagrams produced during these activities then guided the detailed design of a second paper prototype, which could easily be implemented as a functional prototype. The functional prototype facilitated evaluation of real use of the system.

Both the design and design process were based on a model process that is described in the literature. The approach was useful in breaking down the complexity of the design task. The model design was used as the basic idea for our design. This was useful although we made some deviations.

While the conceptual idea of the Mobile Power Plant Communicator and the overall interface design proved useful and was embraced by workers, the usability issues have to be addressed and further evaluations carried out before a final design can be reached. Longitudinal evaluations in the field would be interesting for investigating into the long-term use of such mobile information and communication systems in an industrial domain. It could also be interesting to explore a combination of predefined messages and traditional audio to handle exceptional cases as well as new means for communication such as image and video.

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