High-Octane Work: The oil and gas workplace

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Abstract. This paper introduces the oil and gas workplace context and describes work practices observed at a large Norwegian gas refinery. Ethnographic fieldwork was carried out over a ten day period, consisting of observational studies and informal interviews. They are a small, inter-disciplinary group who are highly mobile and work in a hazardous, critical environment where mistakes can pose risk to health, safety and the environment as well as significant financial loss. Two main shift roles, field operator and central control room operator, are discussed and related to the wider workplace. Even in this technologically-advanced workplace, non-digital informational artifacts are important, often serving as bridges to support flowing activity between communities of practice and the physical and digital. Spending time in the physical plant was seen as an important way to develop an understanding of the process and to gain insight not available through a control system. The primary contribution of this paper is the detailing and discussion of an oil and gas workplace from a CSCW perspective, a context not well established in the literature, yet one that poses an interesting range of design challenges.

Introduction

Oil and gas (O&G) workplaces present manifold challenges for design and seem a promising area of future research. O&G operators are mobile, work in inter-disciplinary teams, in and in-between harsh outdoor and benign indoor environments. They make use of spectrum of tools, from complex ERP (Enterprise Resource Planning) information systems through to rudimentary mechanical tools. Additionally, the refinery or process they attend to is spread over a large space which is both logically and physically complex. High-pressure pipes, extremely low and high temperatures and explosive materials mean the workplace is also a hazardous one, posing risks to human health and safety as well as the environment (HSE). As such, work practices, protocols and equipment are first and foremost designed to promote safety and decrease risk. This naturally impacts what kind of technology can be deployed at a site, for example a normal camera cannot be used without special precautions due to the risk of explosion. Work is of a critical nature: mistakes can cause HSE issues and/or disrupt production, both of which can have a very large financial impact.

Kvasir[1], the studied site, is a refinery situated in a remote area of Norway, supplying a large proportion of the European market and one of many onshore and offshore facilities operated by its parent company. Like most onshore facilities, it is separated into two areas, administration and plant. The three-storey administration building is where regular day shift workers have their offices and also houses the control room, meeting rooms and cafeteria. The plant is where the refining takes place, thus the location of highest HSE risk. It is located 2km from the administration building with workers transiting by vehicle or bicycle. Shift teams' priority is to ensure safe, 24-hour production, while engineers and maintenance staff focus on longer-term upgrades and repair work.

Control rooms featured in CSCW literature have frequently been transport-related, such as air (Bentley, Hughes, Randall et al., 1992), subway (Heath and Luff, 1992) and ambulance (Martin, Bowers and Wastell, 1997). We suggest that the O&G control room is different in two ways. Firstly, there is a significant amount of collaboration and interaction in the O&G control room between people of different disciplines. For example, engineers and field operators might meet in the control room to work through a fault with a control room operator. Furthermore, O&G control room operators have frequent and direct contact with the people they issue directives to (field operators) and work with them in a highly collaborative fashion remotely or co-located in the control room. Secondly, the high degree of automation in O&G facilities mean 'control work' is usually only conducted when something is amiss or when maintenance or repairs are being carried out. As such, control room operators are often idle, particularly on night shifts, yet still need to be attentive and ready to take action.

The industrial workplace - and the O&G workplace in particular - is not well documented in the CSCW literature. We have previously suggested that the O&G workplace has parallels to the (commonly-studied) hospital workplace, which may offer opportunity for re-framing existing studies (Heyer and Grønning 2008). The contribution of this paper is an introduction and discussion of the workplace and its work practices, from the perspective of the shift team who work in and across the industrial environment and the control room. In this publication we do not seek to provide 'implications for design', merely to provide a descriptive account of the context and serve as a resource for future design and research.

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1 Names have been made anonymous.

Future work will report on subsequent field studies at other facilities, and develop a set of general design recommendations and insights for the oil and gas context.

The next section of the paper outlines the methodology, followed by an examination of how work is conducted at Kvasir. A discussion section analyzes observations thematically and the concluding section highlights main findings.

Methodology

Ethnographic fieldwork (Hughes, King, Rodden and Andersen, 1994; Randall, Harper and Rouncefeld, 2007) was conducted over a period of ten days, consisting of participant observation and informal interviews. The focus of the observational study was the shift team, however regular day shift employees such as managers and engineers also participated in the study through semi-structured interviews. Observations were conducted by shadowing a particular participant for a shift, or by observing a particular work area, such as the shift leader's office or central control room. Participants would often volunteer information, describing what they were doing and why and speaking aloud information they received on the radio or computer. It was more likely though that we would ask participants questions as they went about their work to provide explanations and clarifications. Eight different shifts across all three shift periods (day, evening and night) were observed, as well as interviews with 28 people. Notes, photographs and sketches were made during observation and interviews, which were reflected upon and expanded at the end of each day. On the following day, observations were discussed with participants in order to validate their correctness or discover alternative or more detailed explanations.

Work Practices

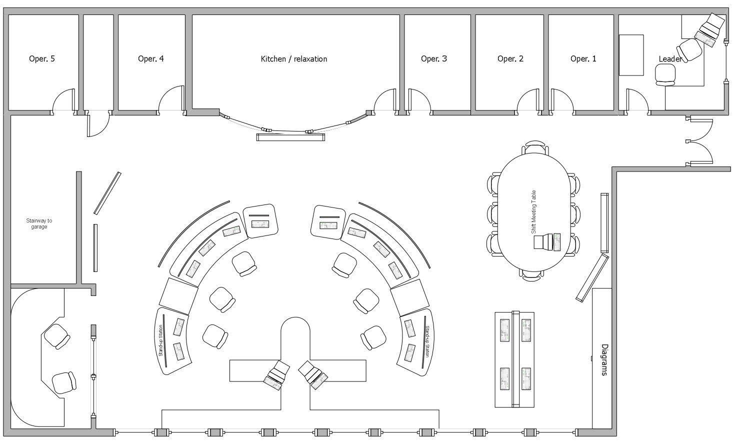

Figure 1. Central control room map. Two control stations are located in the center of the room.

The shift team of around ten people is made up of field operators, two central control room operators and a shift leader and is based in the central control room (Figure 1). Kvasir also has a "day shift" that works regular office hours that includes engineers, administrators and other personnel. The shift leader is a senior member of the shift who manages the team and acts as a mediator between them and the wider organization.

Field operators

Field operators have particular core competencies (such as mechanic or electrician) and are also assigned to particular plant areas. Operators usually work solo as they roam around the plant but frequently liaise with other operators, contractors and engineers. Much of the upgrade and repair work is carried out by contractors, whom the operators oversee, managing work orders and permits as well as ensuring the safety and quality of the work. During a shift, operators also perform maintenance duties, such as draining fluids and cleaning motors.

Field operators have offices adjoining the central control room where they have computing resources and can attend to paperwork. On a usual day shift, operators spend half their time in the plant (Figure 2), half in the administration building. A stairwell from the control room leads straight into a ready room where operators pick up their safety gear and "check in" to the plant with a proximity card. Operators always wear their radio, safety boots and high-visibility, flame-retardant clothes, so they are ready to go to the plant at a moment's notice. When in the plant, field operators have little in the way of advanced technology except for a radio or frequently, a portable gas detector.

Figure 2. A typical oil and gas plant environment.

Central control room operators

Kvasir has two central control room operator roles (CCROs), each responsible for one of two main process areas. From the control system, CCROs can physically manipulate the process, such as remotely controlling valves and pumps. CCROs report that there is usually little need for such manipulations, except in the case of major maintenance or during a shutdown or startup procedure. One operator reported performing manipulations in order to better understand the process, “to see what would happen”.

In their role as a hub and mediator of information and control, CCROs exhibit a high degree of multitasking. For example, we observed an operator who was on a personal mobile phone call also juggle multiple landline calls, radio communication with field operators, radio communication with a moored ship and also making process manipulations – all within a two minute period. Each operator sits at a control station (Figure 3) which has a large projected composite display positioned above and behind four individual screens, all of which predominately show process graphics. Process graphics are a visual depiction of some part of the logical process, overlaid with live process values such as pressures, temperatures and flow. The large display’s abstracted, simplified view and physical size makes it easy to see important information at-a-glance. During emergencies or shut-downs the screens are a useful way of keeping a number of people informed about critical parameters without interfering with the CCROs.

Figure 3. A control station.

Smaller displays are set to show areas of current interest and used to perform process manipulations. Surrounding each process graphic screen is an interface to browse or go directly to particular areas of the plant. In some configurations, panels also appear in the display, for example a list of alarms or video camera feeds. Temporary, overlaid dialog boxes can also be shown, most often for detailed trend line views or ‘faceplates’. Faceplates are used to view detailed information and make adjustments to particular pieces of equipment, with each major class of equipment having its own specialized interface. Three separate computers provide the graphics for the control station's five screens, each with its own keyboard and mouse. This can cause some confusion when moving between the boundaries. Attention can switch quickly to a new screen simply by glancing, while a higher level of cognition is required to release and reacquire input devices. CCROs deal with by attempting to keep the three sets of input devices in spatial relation to their respective displays, to mixed success.

Training, learning and understanding

Field and control room operators both undergo extensive training before being able to work on their own. The training process is a combination of theory learning and apprenticing, with skills being honed and maintained by way of examinations and running through simulated scenarios.

Field operators report that it takes about one year to gain an understanding of a single plant area, perhaps four to five years for the whole plant. Control room operators have a two-year training period before being able to operate a control station solo, and they report that it takes an additional two years to get a good sense of the more complex of the two control areas. Learning periods are dependent on how stable the plant is: an unstable plant is a better teacher than a stable plant. During learning, operators develop an internal model of how the plant works and how the individual components function and fit together to form the process. Both operator roles will have memorized a large number of tags (an identifier assigned to each component of the plant, such as pipes, valves and compressors and used as a uniform referencing system). For a tag number, such as '0300GTFC1AK', an experienced operator knows what it is, where it is located, its history, expected behavior and other properties.

While training provides theory and practical skills, it can still take time for operators to get an understanding, or 'feeling' for the process, a sense of knowing appropriate process values, sounds, smells, vibrations and when things are out of place. Novice CCROs tend to browse process graphics more, as they are not sure which areas to focus on and don't want to miss anything, while expert CCROs tend to jump directly between a small set of graphics. Maintaining an understanding of the process and its operation requires time in the simulator as well as also running the process. For this reason, it is not possible to keep a large number of people 'current' as a CCRO. After returning from the shift's break period (once every six weeks), control room operators run through scenarios in the simulator for around four hours before resuming active duties. Some also read through a log of events to get a sense of what has happened in the plant while they were away. On the first shift back in control, operators report feeling somewhat overwhelmed by the amount of data and alarms, although using the simulator reduces the period of this sensation.

Inspections

Both operator roles conduct regular observation rounds per shift, using their understanding of the plant's norms to detect irregularities. Control room operators conduct their round by traversing the process graphics with their mouse, looking for anything out of the ordinary. By setting their multiple screens - sometimes up to 13 discrete displays - to show particular areas of the plant, the CCRO can be peripherally aware of activity around the plant. Field operators conduct their round by walking through their part of the process, checking oil levels, looking for leakages and so on. This takes an experienced operator around 15 minutes and is conducted thrice per shift.

The 'pull' mode of fault detection is complimented by a 'push' mechanism. For control room operators, this takes the form of control system alarms (Cauvin, Cordier, Dousson et al. 1998) forcing the operator to examine a particular part of the process for sign of fault. For field operators, the 'push' usually comes via radio, for example a control room operator or contractor making a request. For both, these events occur unexpectedly and can interfere with existing work at hand as they usually require immediate attention.

Ritual and routine

Work is ritualized for safety and quality reasons. As an illustration, consider the scenario when a pump needs to be disconnected so it can be cleaned. One operator (with electrical competence) picks up the isolation form from the shift leader's office and travels to the pump's location at the plant. Once there, she verifies the tag number on the paperwork matches the pump in front of her. She depresses the manual stop button and pins a white copy of the isolation form to the pump. At the appropriate electrical substation, she finds the switch panel for the pump as well as a padlock for the panel. The handle is switched into the off position and the padlock inserted to prevent it being turned on inadvertently. It is critical that the right switch panel is isolated and that it does not get reconnected while someone is working on it. A red duplicate of the form is attached to the panel and the key is put back in the cabinet, or given to the person working on the isolated equipment if they request it. After the inspection is completed, the operator is called down again to reverse the process, step-by-step. Each step is ritualized and formalized so all parties can be sure the process is carried out correctly and safely. The paper copies of the isolation form pinned on the equipment and switch panel serve as visual notifications of the alteration and that protocol is being followed.

Situated action

There is usually some amount of pre-determined structure and activity to operator's work, such as routine inspection or maintenance, depending on the prevailing plant conditions. However, we suggest that most of field and control room operators' work is reactive, based on emergent conditions and activity of others. For example, a field operator might be performing an inspection round, and then be radioed by a contractor to approve that the work site is safe to commence work. The operator interrupts his current task, travels to the contractor and signs one part of the work permit. He then resumes his work, but will be likely interrupted again when the contractor radios again for the final signature when the work is complete. Field operators are also frequently issued commands and requests from the control room, such as to perform isolations, check valves and so on. Because requests are ad-hoc and not centrally triaged, it can result in inefficiencies. For example, we often observed an operator driving down to the plant and start work, but after receiving a radioed request need to travel back to the administration building to pick up a form, and then drive back to the plant.

Collaboration and communication

Kvasir is a small organization of approximately 130 employees with a relaxed, informal atmosphere. The flat organizational structure results in short lines of communication and it is typically easy to directly communicate with the required people, regardless of their organizational division.

Technologies

A patchwork of different technologies are employed for collaboration and communication. Computer-based systems include the ERP system, web-based document management systems, email and instant messaging. Radios are mostly used to communicate between shift members and to on-site third parties such as contractors and ships. Wide-area broadcasting is accomplished using the public address system, installed in the administration building and the plant, however considered ineffective in the plant where loud noise and hearing protection occludes the speakers.

Mobile telephones are pervasive, however because they introduce an explosion risk, are only permitted in the administration building. Some employees carry three mobile phones: one personal, one company-issued work phone and another company-issued emergency phone. Those with an emergency phone are expected to have it with them at all times, even after hours, so they are reachable in case a problem arises. Although most people are reachable through a phone connection (be it fixed or mobile), it is seldom used between people at Kvasir, as face-to-face communication is preferred.

Radios are the predominate medium for mediated communication between shift members. Under normal circumstances, around 20 people are tuned to the main channel used by the shift. In the plant, operators wear helmets with integrated ear protection and headphones, by connecting the helmet to their radio they can reduce background noise and hear the radio clearly. A microphone and button is integrated into the cable so the operator can speak while leaving the radio clipped to her belt. There can be issues with radio congestion, especially during periods of intense activity such as during a shutdown, although operators report that normally it is not a problem. Radios provide a shared awareness for the entire shift, as everyone can hear the broadcast utterances which reflect location, activity and progress of each member. Shift leaders note that a sophisticated presence or location awareness system is not needed because simply listening to radio chatter tells them much of what they need to know.

Cross-talk, static and high background noise can impede hearing of radio communication. Instructions and numbers (such as new set points or tag numbers) are repeated back to ensure correctness. Operators will also physically move away from particularly noisy areas in order to better hear the radio, although normal conversation volume is usually sufficient when speaking. The volume of the radio is continually manually managed, for example in the administration building, operators keep the volume low, selectively turning it up when they hear something that might be important. In the field, a higher volume is used which can surprise operators when returning to the administration building with their headphones disconnected. Likewise, operators sometimes forget they've turned their radio down, with the whisper-volume of the next transmission acting as a prompt to turn it up again. When talking with people face-to-face in the field, operators constantly alter the volume to zone in and out of the radio chatter and balance hearing the person next to them with hearing the radio, another form of boundary management.

Many informants reported not using instant messaging "as much as they should", acknowledging the benefits of instant messaging (asynchronous, quick communication), but preferring a short face-to-face chat. Instant messaging is often used as a support for face-to-face conversation, for example sending hyperlinks and tag numbers through instant messaging prior to visiting someone. It was also used for quick, simple inquiries, such as a control room operator asking the shift leader for a clarification about a work order. Most IM communication took place between employees who had a reasonable amount of personal familiarity. For unknown persons within the wider company, participants reported they were more likely to use email or telephone.

Email was used when a digital artifact was needed to support the communication, such as an attached document, or when a higher degree of formality is required. Email is also preferred when a single communication needs to be distributed to multiple recipients or when an audit trail is desired.

Face-to-face

As a result of a small, informal workplace, a significant amount of communication takes place face-to-face. One informant reports that he prefers to pick up a coffee and meet someone for a chat rather than arrange a formal meeting or communicate via a technology-mediated method. Impromptu “drop-ins” aren’t successful when people are out of the office, however. To deal with this, people check others’ instant message status to see if they appear to be in their office or send a message asking if they have time to chat. Several informants reported being annoyed at not knowing people’s availability well enough: time can be wasted if a person goes to visit a colleague, but she is not there. On the other hand, one informant reported quite enjoying the excuse to get out of his chair and go for a walk, and didn’t see these missed connections as a problem.

Kvasir has an open-door policy, which encourages communication but also disruption. Informants report different experiences with this policy. For some, this open door policy can be more disruptive than it is helpful, as their work is constantly interrupted by a stream of people at their door. Others find it very helpful to be able to directly visit and ask someone a question quickly without having to make formal arrangements. Clearly a balance between these experiences is desired and even those informants who were often interrupted thought it was a worthwhile policy overall. Hallway-facing walls of offices have large glass panes which facilitate awareness of office activity and presence.

Intra-shift

Shift meetings are held at the beginning of each shift at a desk in the control room. The shift leader chairs the meeting and operates the meeting computer, the display of which is also visible on a large screen behind him. Using the ERP system, the shift leader runs through the digital shift log, a list of current issues with the plant. Issues which are new to the shift or have undergone change are focused on, with long-running outstanding issues largely ignored.

Because of the consistent shift composition, shift members recognize each other’s voices on the radio which aids communication. Members know who is responsible for which area for a given shift period, so people are normally summoned by name (“Anders?”) rather than by role or responsibility (“Control room?”). Interaction can also take place wordlessly, in one situation we observed a field operator walk in to the control room and sit next to a CCRO. Without a word, the CCRO, aware that the operator was just working on a pump, switches graphics on a screen to show the pump in question.

Intra-day shift

Formal meetings between day shift workers takes place in dedicated meeting rooms, or rooms with added meeting-support technology. An example of the latter is the maintenance office, which has a large wall-mounted display that the maintenance leader uses to send a clone of his desktop to so that others can follow along as he navigates through defect notices. Meetings usually take place around computer-based output, be it an on-screen application or slide deck, with the ERP system widely used as a way of navigating and presenting data. There are difficulties with this approach as the program was not designed for presentation, especially not on a large screen.

In a recent change, some Kvasir management personnel now report to management located in distant cities. Collaboration takes place over instant messaging, email, phone calls, and increasingly, video conferencing. Naturally, these types of communication and collaboration are not well suited to the informal style of interaction that is commonplace at Kvasir. Informants noted that it was thus harder to maintain personal ties and feel connected to those located remotely. Travel to either of these locations is also difficult due to Kvasir's remote location and requires a significant amount of time.

Central control room operators

Although the two central control room operators sit in close physical proximity there appears to be little collaboration between them. Partly, this is because when the plant is running as it should, there is little to work together on: they share a role, but rarely share tasks. The alarm list which appears on both operator's large screen (and often duplicated on a small screen too) is shared. As alarms occur, an audible tone is produced and a new entry appears at the top of the alarm list. Operators use the mouse to mark an alarm as acknowledged; collaboration can thus take place around this shared alarm list. Operators do not manage alarms which are unrelated to their part of the plant, however they serve as a useful peripheral awareness as to their colleague's activity and status. Alarms might not be directly related to their part of the plant, but because of the interconnected nature of the process, may have an impact if the situation is not managed. Thus, if an operator notices her colleague's unacknowledged alarm list growing she might ask him how he is going, or simply look over to his desk to gauge his activity. There are different styles of alarm management which can cause some mild tension between operators, for example, some acknowledge alarms as they occur while others prefer to process alarms in batches.

Engineers and the shift

Engineers draw up work orders which are carried out by operators or contractors. A work order might be simple, such as modifying a pipeline's pressure, re-routing flows or more complicated upgrades and repairs. The central coordination artifact for such operations exists in digital form in the ERP system but is regularly printed throughout the workflow. Engineers will occasionally visit the person responsible for carrying out the task with the printed work order, sketches and annotated diagrams in hand, to talk through the plan. Operators have a rich practical understanding of the process which complements the engineer's theoretical perspective. Engineers noted that operators will often suggest an alternative plan which achieved the same result but was easier to implement. It is important for the engineer to ensure that the operator understands the work plan or shift instruction and some engineers suggested that this was easier to accomplish face-to-face.

Engineers and operators also occasionally work around the stand-up stations, or at the main control stations. For example, an operator might pull up the process graphics for a particular system and use that as a basis for conversation with the engineer, highlighting particular process values using trend lines. The stand-up stations, more so than the control stations, encourage collaboration around the data, and there were a number of occasions observed when operators or operators and engineers worked together around the screens.

Many engineers make a point of regularly visiting the control room to maintain a good relationship with the shift and to pick up on issues unreported through official channels. It also provides an opportunity for the shift, which is largely bound to the control room and plant areas, to informally and directly interact with the engineers. Sometimes these visits might amount to little more than drinking a coffee while hovering near the control station, or perusing process graphics at the stand-up station. More often than not however, conversation would be initiated and news and updates exchanged. One engineer also reported it being useful to talk face to face as some things are not well expressed in written communication. Engineers also note that the frequent contact is useful for building up two-way trust and better understanding of each other's competencies.

Remote communication between operators and engineers is usually via email, partly due work period mismatches. It is also because communication often includes hyperlinks, documents and precise numbers which need to be expressed clearly and in an auditable manner. For urgent issues, operators will send a text message if they don't expect the engineer will check their email soon. Shift leaders also maintain close ties to engineers and will often call them down to the control room for consultation.

Information and systems

In the plant, various informational artifacts are used to situate temporal information to a particular location and piece of equipment. For example, when a valve is manually changed from its normal operating state, a large plastic sign is attached. It has a "blinding" number written on it in temporary marker that cross-references a printed list kept in the shift leader's office as well as in the ERP system. The tag number, date and who made the change is also written on the sign. During maintenance rounds, paper tags are used by operators to keep track of which equipment they have inspected, usually with only their initials or a date written on them. Once the round is complete (perhaps over several weeks), the tags are taken down. Operational transactions such as isolating an electrical circuit can also result in temporary notices being pinned to different equipment.

The ERP system is the primary common information system (Bannon and Bødker, 1997), integral to most aspects of work at the refinery. For example, if an operator notices a defect at the plant, this is entered as a 'notification', which is then reviewed and annotated by the maintenance network, and possibly goes on to form the basis for a work order and work permits. Information is extensively cross-linked, for example when reviewing a work order, it is possible to see if required parts are in stock, retrieve product specification information or diagram the fault in the context of the logical process. New informational artifacts or exchanges are often composed from disparate sources, such as collating diagrams, specifications, notes, instructions and annotations in a work order. Like Fitzpatrick's (2004) observation of hospital patient records, these composite, multimedia, locally-contextualized artifacts are "living documents" which frame and support work activities rather than being a passive information repository.

Piping and instrumentation diagrams (P&IDs) are perhaps the most important reference document in the oil and gas workplace, or as one operator called them, "our bible". In the diagrams, a logical view of the process is shown similarly to the on-screen process graphics but in greater detail. They are often referred to when there is a need to isolate a section or to trace through the process. Operators with different competencies read the diagrams differently. For example, some read the diagram for valve details, while others read it for the properties of pipes (such as the type of steel and pressure class).

P&IDs are drafted and maintained on a computer but the canonical version of a P&ID is the printed master copy kept in the control room. They are updated over time to reflect alterations in the plant – these too are living documents. Diagrams are frequently printed, which enables them to be physically attached to a work order, carried to the plant or around the building, or used to support discussions. Reading diagrams online in PDF form is common and considered a useful and viable alternative to paper-based diagrams. Diagrams are usually sparsely laid out and thus do not demand the high resolution that paper affords. They are hyperlinked so that the user can navigate the process or retrieve further detail by clicking hotspots. This is considered one of the more useful aspects of electronic viewing – the ability to explore the process with minimal effort. When using printed diagrams, the user would need to know what part of the plant to print and at what detail, and there is a time penalty of finding and printing or retrieving the diagram if another view is required.

Vignette: Dealing with pressure

To illustrate the collaborative work and use of informational artifacts by the shift, we describe the following event which took place during an evening shift:

> Suddenly the irregular audible warnings sounded continuously. Soon afterwards, the pitch becomes higher, indicating the warnings are now alerts. The alarm list on the control station blinks frantically as new alarms are rapidly appended. Across the operator's smaller screens, various displays blink urgently. Two field operators come in from their offices, standing behind the control room operator whose area is being affected. The CCRO had not seen this type of alarm before and was a little worried. He also knew from experience that problems in this process area can shut down a boiler which would be a significant problem. On the control system, he quickly opens trend line displays relating to the boiler, scaling them back in time to look for sudden changes. On seeing that the boiler was not being affected, he relaxes somewhat. One operator returns to his office, the other stays and helps the CCRO as the event unfolds. While the boiler did not appear to be affected, pressure was being built up in the distillation column, which would need releasing urgently. P&IDs are brought up in PDF form on the workstation, and quickly printed out. The operator fetches the printed document and he and the CCRO talk around it, trying to establish what is going wrong and how to reduce the pressure. The CCRO's first thought was to relieve pressure via the flare, but after examining the P&IDs and current process values, it would seem as though several valves are in the wrong positions and that the flow could be routed back into the process normally. They then go to the shift leader, an expert in the distillation area, who agrees with their course of action. A field operator is radioed to make changes to the valves and shortly afterwards, everything returns to normal. The entire activity took no longer than 25 minutes, 10 minutes of which was highly tense whilst the alerts sounded continuously.

As a result of flow re-routing during repair work, parts of the plant that have lain dormant for nearly 10 years were used and an error in the original valve diagram was discovered. After addressing the immediate problem, the CCRO composed an email to the responsible process engineer. He attached a screenshot from the erroneous P&ID with mouse-drawn annotations and included hyperlinks from the ERP and web-based documentation system.

Discussion

Non-digital informational artifacts

As described earlier, temporary in-situ notices are used in order to link status information to the physical plant, for example that a valve has been changed from its normal state, or a circuit has been disconnected. Notices are almost always explicitly linked to a particular piece of equipment by a tag number, the universal referencing system in a plant. Notices serve two main purposes: to make visible that which is invisible and to link the physical with the digital. For example, that a valve is in a changed position is not externally observable without prior knowledge of its proper state. Hanging a sign on it makes it clear to everyone that it is currently in an altered state. Because of the enhanced visibility, the valve will also be easier to find when it comes time to changing it back. Moreover, notices express *purposeful* action. If a pump was found to be switched off, the presence of a sign hanging on it will indicate that it was intentionally put into that state.

Digital-based information, such as work orders and reported faults are linked to the physical artifacts by way of the signs. Each notice has an identifier in addition to the tag number which allows people to trace why an action was carried out and other particulars. Brief information is also included on the notice itself.

Sticky notes were only occasionally used for inter-shift communication, such as the night-shift leaving a message asking if a pipe should be running at its current pressure. During a shift, paper was used differently depending on plant activity and operator's experience level. Some maintained pads of paper to keep track of process values and reminders, while others remembered everything: for some entire shifts control room operators would not use any informational artifacts beyond the on-screen process graphics.

Most field operators use a pocket notebook of some type - usually rather tattered - in which they keep notes, tag numbers, part numbers, test results, sketches and so on. Notes range from being highly temporal, written down but meaningless after an hour, to notes which were referred back to years later. Notebooks are often used as an intermediary to the control system, an aid for discussion (such as drawing a picture) or memory.

Plant piping and instrumentation diagrams are useful to locate tags and understand the process. A single plant is represented by hundreds or thousands of P&IDs, available digitally but frequently printed out on an on-demand basis. The A4- or A3-sized pages can then be studied and marked up with highlighters and pens, and is often used as the basis of interaction between colleagues. The diagram is eminently portable and does not introduce a safety hazard in the plant where it is used to identify physical assets or as a navigation or memory aid. For example, whilst in the administration building with full documentation available to him, an operator might highlight on a P&ID valves that need altered and then use this annotated diagram as a spatial workflow to carry out the tasks when at the plant. Engineers also use P&IDs extensively. Marking streams, valves, flows and values on the printed diagram is a way of building an understanding of the process and a useful part of the diagnosis process for engineers, whether working alone or with others.

Perhaps the most prominent use of paper is that of work permits. Work permits have a short lifespan – typically no longer than a day – and are linked to a single unit of work being carried out in the plant. They are an important part of the audit trail, to not only ensure that work is carried out properly, but that it is done in a safe and verifiable manner. Usually a contractor carrying out the work will produce the permit, which is first signed by the shift leader. Some types of work (those with a higher risk category) might require additional signatures before work can commence, such as from the operator responsible for the area. When work is complete, the contractor signs and then the operator responsible for the area signs, taking the permit back to the shift leader's office for archiving.

Signing pen-on-paper is quick and accessible with the only requirement being that the parties and the paper are co-located. Typically, contractors achieve this by radioing for operators when they require a signature, however this can cause delays if the operator is some distance away. Because operators usually need to verify some aspect of the physical scene before signing, the co-location requirement of pen and paper is not necessarily an inconvenience. Co-location can also be achieved somewhat creatively, for example signing forms through open car windows, as one car heads up to the administration building and one heads down to the plant.

Bridging boundaries and flowing activity

Boundaries between systems, people, knowledge, perspectives, practice, groups and locations are bridged in a number of ways. For example, field operators often act as a bridge to the physical process for engineers who do not visit the plant as often. Shift leaders act as bridges between shifts, exchanging information about what has happened during the outgoing shift so the new shift is up-to-date. Artifacts can also act as bridges, in a similar manner to "boundary objects" (Star, 1989; Lee, 2007). Indeed, the sole value of some artifacts appears to be their bridging quality.

Sticky notes are a common example of a bridging artifact in the workplace. Short snippets of information are jotted down and then either pinned up, to inform later shifts, or handed over, for example to exchange a tag number. Their value is often highly temporal, serving a purpose as a bridge in an interaction and then no longer being useful. During maintenance network meetings, work order numbers are often passed to the network leader via instant messaging as the meeting progresses, an even more temporal form of sticky note.

P&IDs serve an important role in bridging the communities of practice (Lave and Wenger, 1991) of engineers and operators, as one engineer reported, "[we] mainly talk with diagrams". The diagram serves as a common foundation upon which new understandings can be built. All parties know how to read a P&ID, and it is through the P&ID that a meaningful discussion can take place, grounded in the common understanding. The diagram also facilitates talking about a process which is physically and logically large and complex through a standardized, simplified proxy.

A common quality of the aforementioned artifacts is their ability to bear free-form expression and direct interaction style. A sticky note and P&ID can have anything written or sketched on top and an instant message can hold free-form text. They are also direct in that they require minimal preparation to use and there is little interactional work required beyond that to express the desired message. These qualities are not found in Kvasir's web- or ERP-based systems, which typically involve extraneous navigation and form-filling work.

The O&G context brings boundaries to the fore partly because of the rich, multifaceted ecology in which activity takes place. Consider for example, how field operators transition between perusing interlinked information systems in an office environment, discussing a procedure over a printed P&ID through to opening a valve in a noisy, hazardous plant. In addition to organizational and technical boundaries, there are also explicit policy boundaries which partition and restrict access to physical spaces and infrastructure such as electrical and computer network grids. Practitioners flow their activities across the multitude of boundaries and diverse resources in order to accomplish their work. To some degree the work environment (computer-supported or otherwise) supports them in this task, however we suggest that flowing is largely accomplished through assembling and tailoring appropriate resources by workers themselves.

The plant

Shift members have a strong phenomenological connection with the plant, which has also been observed in the nuclear power plant shift members (Vicente and Burns, 1996). They speak of the freedom of walking around in the fresh air, the sound of the plant, the smells: feeling and knowing. Frequent contact with the plant over a long period of time allows them to learn what is expected and what is not, what equipment is prone to failure and so on. Shift members' deep understanding of the physical plant is unmatched in the organization and a useful resource for diagnosis and maintenance.

During inspection rounds, rather than simply examining dials and gauges, operators engage with the plant in a rich, experiential manner. For example, an operator will take his glove off and hold his hand to a motor to feel for heat and vibration. Operators listen to equipment's noise, observe steam quantity, color of flames and smell for gas leakages or burning oil. Because of their experience and knowledge of the plant, operators can in effect sense when something is wrong: for example, there might not be enough steam being produced, a motor might be too hot, or a pump might be rattling. These environmental, ambient cues are an important aspect of the operator's diagnostic and observational role. Manual observations are used to look for faults which are not revealed by instrumentation and thus invisible to control room operators in their control system. For example, it is simple to monitor gradual wax build-up on a valve through visual inspection, however it is only when a valve has seized up that the build-up is apparent via integrated sensors, at which point the issue could be critical.

Field operators visit the plant more frequently than other employees. On a regular day shift, an operator will usually spend about half their time in the plant.

As such they are subject to the variable - and very often harsh - environmental conditions, with frequent rain, high winds and temperatures as low as -15°C. Operators liked the variety of being inside and outside, likening it to having two different jobs. Inside, they enjoy the sociality of control room, outside, they enjoy the freedom of movement and contact with plant. Informants enjoy the physical aspect of the work, being able to hear and smell the plant and "get your hands dirty". Most control room operators periodically rotate as field operators, and while they enjoy the chance to visit the plant, they dislike the loss of ownership and mastery when they are "only" field operators.

Engineers also note a strong connection with their work and the physical plant. Because engineers do not visit the plant as frequently as for example, field operators, they have a lower level of awareness about their plant area and can easily overlook small-scale faults. As such, they often rely on operators to bring issues to their attention, especially when they visit the plant together. One engineer reports that there is "something special" about being in the plant itself and that doing diagnostics over a video link would not suffice. He notes that a report or account might miss something important and there is not the "personal impression" you get with a firsthand visit. For example, if a leak is reported, he likes to see it to get a sense of its scale, what it looks like and where it is coming from – properties that could be represented in a fault notification, but are unlikely to give the same sense as to actually observe it directly.

Conclusions

The oil and gas workplace presents a rich, multifaceted ecology of action, spaces, information and artifacts in which activity is carried out. While the facility is technologically advanced, various non-digital informational artifacts are used as critical parts of work. In the plant, situated signs are used to express purposeful action, make visible that which is invisible and to serve as a link between the physical and virtual. Pocket notebooks are used extensively to record both fugacious and enduring information. Most safety and quality protocols require paper forms and written signatures, such as work permits.

Boundaries between systems, communities of practice and the physical and digital are bridged a number of ways. Piping and instrumentation diagrams are frequently used as a resource in communication, permitting a higher-level understanding to be reached from the common understanding of the diagram. Pocket notebooks are used to jot down tag numbers or values in the field, which later serve as input when accessing online information at a workstation. Discussions often take place around a particular tag, with sticky notes or instant messages commonly used a way of exchanging these identifiers. Such mundane technologies are well suited to these bridging tasks due to their ability to bear free-form expression simply and directly. As is often the conclusion in CSCW, designers need to give special attention to the mediation of boundaries in order to support smooth flowing of work across diverse physical and digital resources.

Participants cited a strong phenomenological connection to the physical plant. They note the importance of smell, sound, vibration and sights for understanding the plant as well as detecting and diagnosing faults. More generally speaking, the importance of physical presence emerged as a theme, such as engineers spending time in the control room to build relations with CCROs, or field operators spending time in the plant to learn more about its operation and develop a sense of its norms and quirks. This may suggest limits to tele-operation of facilities, or having operators service multiple plants.

The results reported here hint at some danger in implementing 'obvious' solutions. For example, a system to provide digital P&IDs to the mobile field operator would have limited value over paper P&IDs if it does not support annotations, shared interaction, is explosion-proof and usable whilst wearing gloves outside. In another example, the work permit signing process could potentially be made quicker by using mobile devices which communicate directly with the ERP system and do not require pen, paper or radio communication. This, however, would reduce the shift's shared peripheral awareness of each others' activities since there is no usage of the shared radio channel. Shift leaders and control room operators in particular benefit from the awareness the radio channel provides, even though congestion can be an issue during periods of intense work. An apparatus designed to reduce radio congestion and offer alternative mobile communication to the radio would also need to consider how operators today continually manage volume as they pass between different spaces and selectively place the shared channel at their focus or periphery. For example, if text messaging was to be used to support communication, how would the operator know when a message was important enough to focus on without actually diverting attention and reading the message? How would operators exert fine-grained focus-control?

This paper presented the results of ethnographic fieldwork at a gas refinery focusing on the shift team, which consists of field operators, control room operators and a shift leader. The paper's contribution is an initial description and discussion of the work practices in the oil and gas workplace, a context not well explored in the literature, yet one that poses interesting challenges to the CSCW community.

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