Safety in Design

Human factors influencing safe design of a new technology

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Preface

First and foremost I would like to thank my supervisors Karin Laumann and Gunhild Sætren. Both have been most helpful throughout the entire process of setting up my study, collecting data, analysing, and writing my thesis. Their ideas, suggestions, and feedback have always been very welcome and have helped me to keep a positive and assertive attitude towards my thesis project.

Additionally, I would like to thank all my other mentors at the university, for never stop believing in me. And all my friends and family, without their loving support this roller-coaster ride, known as a thesis, would have been boring and frustrating. This thesis project has introduced me to the oil and gas industry and has awakened my interest in human factors. I hope to be able to apply the insights that I take away from this project in my future work as a human factors consultant.

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Abstract

The aim of this study was to explore the role of safety in the design of new technologies in a high-risk industry. For this study 7 interviews were conducted with designers and developers who worked together as a team to develop a new technology for the oil and gas industry. The data analysis was done using grounded theory based on the ideas of Strauss and Corbin (1990). The analysis showed that the interaction between humans and the technology is critical to the safety of the design. Therefore it is not possible to base safe design solely on technical features; latent failures are not just technical. A more holistic approach to safety is necessary when judging the safety of design, and the designer's understanding of the competencies of the end-users is central to this.

Table of Contents

Introduction

The oil and gas industry is a high-risk industry with a high focus on safety (Mearns & Yule, 2009). In spite of the high risks associated with this industry, it has very few major accidents, and is therefore known to be a high reliability organisation (HRO)(Reason, 1997; Weick & Sutcliffe, 2007).

Most of the safety and risk research in this industry has been concerned with the sharp-end (Flin, O'Conner, & Crichton, 2008). Whereas little research has been done on the impact of the blunt-end on safety. The blunt-end includes design teams that are responsible for developing new technologies. These technologies have to be efficient as well as safe. Technology carries several latent conditions that can contribute to cause an accident (Reason, 1997) under the right, or rather under the wrong circumstances. It is therefore of utmost importance that design teams pay attention to the safety aspects of the technology that they are developing. A well-designed and safe technology is the first line of barriers to preventing a major accident.

Therefore, the research question of this study was: *Which factors influence the development of a safe design?*

The aim of this study was to explore the role of safety in the design of new technologies in a high-risk industry. Therefore, this study will explore the design process of drilling equipment based on new technology within the oil and gas industry. Details about the project and the technology cannot be released, due to confidentiality matters. The designing, testing, and implementation of a new technology is a long and cumbersome iterative process, where the different stages have to be repeated until the technology is working properly and safely.

Later, the results will be discussed and compared to several theories related to safety and safe design in order to compare the developed theory to existing theories. These existing theories on safety include human factors in design, general theories about safety and resilience engineering (Dekker, Hollnagel, Woods & Cook, 2008).

The results of this study will contribute to the understanding of the way safety is perceived by designers of new technologies. A safe design is the first defence against threats in operational safety; it will be valuable to know how designers consider safety during the development process.

In the following sections, the theoretical background of safety will be briefly presented before an overview of design, resilience engineering, and human factors in design will be given.

Theory

Theory on design

A design process may be described as developing a structure from a function (Kroes, 2012). This process consists of various phases. These various phases have received different labels by numerous researchers and models. Figure 1 therefore presents only an example of such a phase diagram of the engineering design process. Generally, an engineering process starts with an order from the customer, followed by the creation of specifications based on the order. From there conceptual designs are made and compared, then the best option is developed into a prototype, which will be implemented (Kroes, 2012; Pahl, Beitz, Felthusen & Grote, 2007).

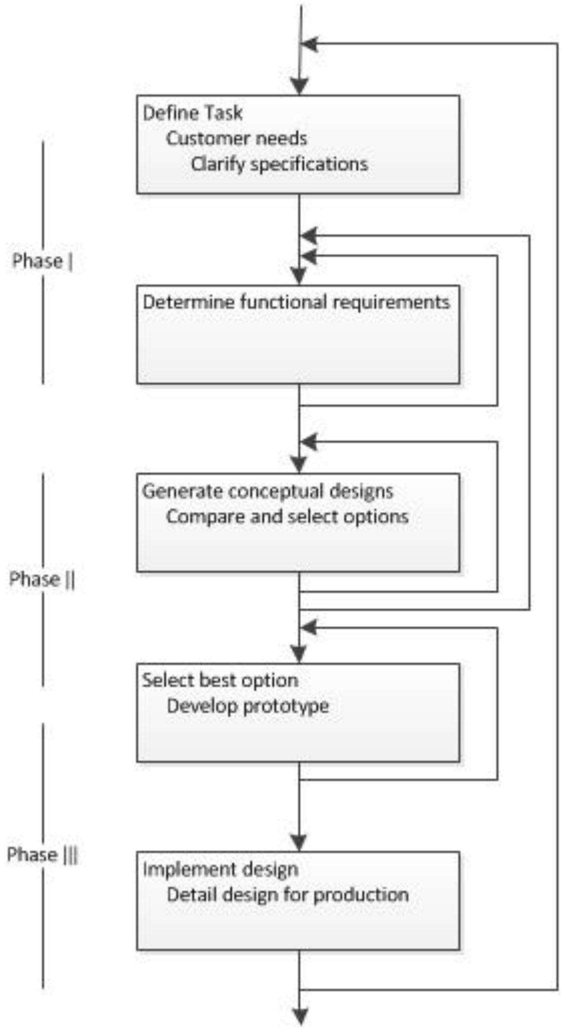

Figure 1. Design process based on Kroes, 2012 p. 138.

For more complex designs these types of models become important for managing the design team and project (Kroes, 2012). However, the way that designers think is not a linear process. Design thinking is usually represented as an iterative process of five stages: (re)define the problem, need finding and benchmarking (including: understanding the users and design space), idea generation, prototyping, and testing. In reality these five stages are not visited in a predefined order. The designers can go from one stage to the next based on experience (Meinel & Leifer, 2010).

Human factors in design

Most new technologies today are still designed without adequate consideration of human factors (Wickens, Lee, Liu & Becker, 2004). The main priority for the designers is the technology, thereby neglecting the usage of the technology from a human point of view. As a consequence, poor design is common. In addition, technologies become increasingly more complex, making them even more difficult to use. If the end-users are consulted at all, it is often after a prototype has already been developed. For a design to reach the state of a prototype a lot of resources have already been spent. The investment in the initial design will make the designer reluctant to change, resulting in a product that is often not suited to satisfying the needs of the end-user (Wickens et al., 2004).

Human-centred design can increase the usability of a system (Norman & Draper, 1986). Usability in its turn is associated with increased productivity (so an operator can focus on the task instead of the system) reduced human errors, reduced training and support, higher levels of acceptance and a better reputation of the system (Maguire, 2001).

In order to achieve more usable systems the human-centred design needs to include both end-users and a clear understanding of the end-user and task requirements. Moreover, a good division of tasks between humans, software and hardware is necessary. Also, using the end-users to evaluate design solutions and incorporate their feedback in the further development of the design, are important for the usability of a system. Furthermore, design is known to benefit from multi-disciplinary design teams (Maguire, 2001).

Even though, human factors have been mostly driven by technology in the past (reactive design approach), in the future human factors should drive technology (proactive design approach) (Karwowski, 2007). This view is complicated by the designer being under numerous constraints, such a cost, time, reliability, safety, environmental impact, ease of use, available resources, manufacturability, regulations, laws and politics (Karwowski, 2007). Human factors and ergonomics are a design-oriented discipline. However, human factors and ergonomic experts do not design systems, rather they design the interactions between the systems and humans.

These interactions have become increasingly more complex due to automation in technology. These complex systems require greater integration from a design perspective, as well as a management perspective (Karwowski et al., 1994). Integration from a design perspective refers to the interactions between hardware, organization, information system, and people. Integration from the management perspective refers to the interaction between the different system elements, such as product quality, workplace and work system design, occupational safety and health, and environmental policies (Karwowski, 2007).

Technological change impacts human factors in the existing design. This means that it impacts the interaction between man, technology and organisation. As a consequence the relationship between these three should be redefined. Technological change alters practices and shifts causes of error and strength. In addition, technological change is found to increase the pressures and requirements of operators even though the intention of the technological change was to decrease demands on the operators (Woods & Dekker, 2000). To re-evaluate the safety of a design after a technological change three theories on operational safety are presented below. These three theories: safety culture, high reliability organisations, and resilience engineering, all postulate different views on what makes an organisation operate safely.

Safety and safety culture

In organisations safety is a trade-off between protection and production. The capital of an organisation needs to be invested into production to keep the organisation safe from bankruptcy. However, if the organisation solely invests in production and not in protection, then the organisation is unprotected from catastrophe, and is also unsafe (Reason, 1997). Many hazards threaten the safety of an organisation and its employees, especially in high-risk industries. To prevent those hazards from harming an organisation's assets, barriers need to be installed to create defensive layers in the technological systems operated by the organisation. Nevertheless, Reason (1997) postulates that all defensive layers have weaknesses, creating holes in the defensive layers.

Furthermore, Reason's (1997) Swiss Cheese model is a metaphor for the defence system of organisations, the defensive layers with holes in them are flux and the holes can appear and disappear. These holes are created by active failures and latent conditions. The active failures are caused by the sharp-end committing unsafe acts; the latent conditions are created in the blunt-end, for example by a bad design. Neither active failures, nor latent conditions, necessarily need to result in accidents, but they hold the potential of contributing to the cause of an accident (Reason, 1997).

Safety culture is seen as an aspect of the broader concept of organisational culture. Much like organisational culture, it is presumed to be a relatively stable construct (Cooper, 2000). Safety culture arose after the Chernobyl accident in 1986 and the Piper Alpha incident in 1988 (Pidgeon, 1998). The Confederation of British Industry (CBI, 1991) described safety culture as “the ideas and beliefs that all members of the organisation share about risk, accidents and ill health”. Schein (1992) said that safety culture relies on core underlying assumptions, which are taken for granted by the whole organisation, adopted beliefs and values, and behaviours and artefacts. These definitions of safety culture are relatively similar; they can be classified into a normative beliefs perspective (Cooke & Rousseau, 1988). All definitions focus on the way people think and/or behave in relation to safety.

Also, Pidgeon (1998) describes a paradox of safety culture. He suggests that while safety culture can make people aware of some hazards, it draws attentions away from other hazards. Nevertheless, there are such things as a bad and good safety culture. Bad safety culture is characterized by: higher error rates and accident levels, failing to communicate appropriately about risk, and wrongly handling new hazards (Health & Safety Executive, 1993). A good safety culture, on the other hand, is associated with: communications based on mutual trust, shared perceptions of the importance of safety, and the positive attitude towards preventive measures (Health & Safety Executive, 1993).

Furthermore, Reason (1997) identified four important components of safety culture, namely a good reporting culture, a just culture, a flexible culture, and a learning culture. A good reporting culture is characterised by trust. The employees need to know that the information they are sharing is dealt with confidentially, that there are benefits to reporting, and that reporting is meaningful. A just culture is defined by considering the intentions behind actions as well as their consequences. A flexible culture is tolerant and flexible when it comes to, for example, task descriptions and meeting places. Lastly, a learning culture is characterised by being able to detect and react to signals of hazards in a rational way, even when the signals are not easy to interpret. Information should be shared both horizontally and vertically in the organisation and the communication should be clear (Reason, 1997).

Resilience engineering

Resilience engineering does not view safety as the absence of error or incidents, but rather the safe practice of people operating the system throughout all levels of the organisation (Dekker et al., 2008). It is a new way of viewing safety that is different from the more standard risk management approaches, which are based on concepts such as error calculations, violations, and failure probabilities. Resilience engineering emphasises the organisation's ability to adapt to the complexity of the real world. It operates on the assumption that organisations need to monitor and revise risk models, while creating processes that are both robust and flexible. In addition to having a proactive attitude towards resources once faced with disturbances or pressures related to production. Resilience engineering focuses on what sustains or erodes the adaptive responses of a system under changing circumstances (Dekker et al., 2008).

High reliability theory and resilience engineering have a lot in common. They both have adopted a rather proactive strategy when dealing with hazards (Hollnagel, Woods, & Leveson, 2006). When compared to high reliability theory resilience engineering stresses that reliability is not synonym with safety. A system or organisation can be reliable, but that does not make it safe. Whereas high reliability organisations still use risk management, resilience engineering uses safety management (Dekker et al., 2008).

Method

First the project this thesis was a part of, will be described. Thereafter, I will elaborate on the choice of methods that were used to analyse the data, the research design and selection of interviewees. Additionally, the process of creating the interview guide and conducting the interviews will be described. Furthermore, an explanation of the data material and analysis will be given. Finally, some concluding remarks about ethical considerations will be made.

Project

This master thesis is a part of an on-going project called the e-centre Laboratory for Automated Drilling processes (eLAD) project. eLAD is a project financed partly by the Norwegian Research Council and partly by the oil industry. There are three collaborating parties in this project: International Research Institute of Stavanger (IRIS), Christian Michelsen Research (CMR) in Bergen and Institute for Energy Technology (IFE) in Halden. These institutes are linked through "Energialliansen", with the intention of utilising complementary competences.

The objective of the eLAD project is to build laboratories and facilities to be used for developing, designing, evaluating, and optimizing future e-centre based working processes, software tools and automation processes. This is done in order to provide a unique environment for safe experimentation throughout the planning, and execution of drilling operations.

Choice of method

Based on the research objective and question in this study a qualitative approach was chosen. Moreover, due to the lack of previous research on this topic it was decided to use grounded theory as the specific qualitative approach, and semi-structured interviews were selected for data gathering.

Qualitative research interview. A semi-structured interview is also known as qualitative research interview (Kvale, 2007). By choosing a semi-structured interview as opposed to a structured interview design, there was room for the interviewee to steer the interview into the direction of his or her interpretation of the topic (Kvale, 2007). This data gathering technique is frequently used in qualitative studies (Kvale, 2007), and complements the chosen methodology, grounded theory, well. To fulfil the research objective of this study and gain more insight into safety in design in the oil and gas industry, several topics related to safety and design such as teamwork, communication, automation, and responsibility, were discussed in the interviews. These topics can be found in the interview guide.

Methodological approach: Grounded theory. Due to the fact that at the beginning of the thesis project the researcher did not have much prior knowledge about the topic, and the lack of development about this specific topic in the field, the study was considered to be appropriate for grounded theory by Strauss and Corbin (1990). By using this qualitative method, I developed, discovered and confirmed my theory through systematic data collection and analysis (Strauss & Corbin, 1990). The process of grounded theory is more circular than linear, and it uses both deductive and inductive thinking to let the theory emerge from the naked data. By using the techniques of coding, concepts, categories, saturation, and memos, I eventually developed a theory (Strauss & Corbin, 1990). Ideally, the researcher should be coding during the data gathering, and should be able to go back to his or her original sources, the interviewees. I followed the interpretation of Strauss and Corbin of grounded theory and used their guidelines to analyse and treat the data material. However, the data collection was restricted by the limitation of this study and its participants. Therefore, I decided to follow the guidelines of grounded theory as closely as possible and adapt the interview guide based on the previous interviews, and accepted that I would most likely not be able to go back to the interviewees with further questions.

Research design and selection of interviewees

This study set out to develop a better understanding of safety in design of new technologies. Since this study is part of the eLAD project there was one particular new technology that could be examined, and therefore this study was designed as a case study of the design of that technology. A case study is an analysis of a single unit (e.g., a person, group, process, or object) focusing on the developmental factors of that unit in relation to the context (Flyvbjerg, 2011).

The interviewees were selected based on the selection criterion that they had been involved in the design process of the new technology. This was a limited sample. To enable comparisons, subjects were selected from different companies that contributed to the design project in different roles, the customer, the contractor, and a subcontractor, and in order to confirm their statements more than one interviewee was selected from each company. The selected interviewees were contacted via email, where an explanation of the research project and the objective of the master thesis were also given. They were asked to participate in an interview that could either be conducted via telephone or videoconference, based on the preference of the interviewee. Recruiting participants was difficult due to the busy work schedule of the sample. The study included interviews with 7 interviewees.

Creation of interview guide

The interview guide was semi-structured, which meant that it had a fixed set of questions deemed relevant for the thesis' topic and objective (Kvale, 2007). The interview guide was created based on brain storm sessions with my supervisors on which themes could be interesting to further develop the understanding of safety in the design of new technologies. Due to the requirements of grounded theory regarding the naivety of the researcher I did not submerge myself in the literature surrounding this topic during the development of the questionnaire (Strauss & Corbin, 1990).

The interview guide that was used for this study consisted of three main categories, namely the work process, safety, and the end-users. Each category had a number of subcategories, which included more detailed questions. Furthermore, the interview guide was discussed after every interview with one of my supervisors. During these discussions it was decided whether we needed to adapt the interview guide based on our observations of the appropriateness of the questions, the flow of the interview, and the answers that the interviewees gave.

Conducting the interviews

The interviews were conducted in Norwegian or English (depending on the preference of the interviewee), either over the telephone or videoconference. The interviewees were sitting in their own respective offices where they would not be disturbed for the duration of the interviews. These set-ups were chosen so that they were least inconveniencing for the interviewees (Kvale, 2007). Moreover, the interviews were recorded with an audio-recorder. The participant was notified before the start of the interview about the use of the recorder and was asked for consent. The interview only started after the participant had consented to the recording.

During the interviews the interview guide was mainly used as a guide to ensure that most of the main topics were discussed and as a red thread throughout the interview. However, when an interviewee digressed from the topic with an interesting thought, this was further explored. This allowed for insights to develop, which would not have been possible in a non-semi-structured interview (Kvale, 2007).

Data material and analysis

After the interviews were conducted, they were transcribed, and my supervisor checked the transcriptions to ensure that no data was left out or wrongly noted. The transcriptions were anonymized to ensure that information from the interviews could not be traced back to the source.

The coding and analysing techniques used in this study were developed based on the Strauss and Corbin's (1990) interpretation of grounded theory. NVIVO was used to code the data. The interviews judged to be richest were first coded using line-by-line coding. This method was chosen to make best use out of those rich interviews. This was done for four interviews; thereafter the remaining interviews were less rigidly coded with focus on themes that had not come up in the other interviews. After all interviews had been coded, they were further analysed and sorted into categories. These categories were formed using the guiding question of what the codes had in common. Based on a combination of inductive and deductive thinking these categories were reassessed and categorised on a higher, more abstract level. Throughout the process categories were compared to the original data material to decide whether the category was valid, and memos were written for future reference (Strauss & Corbin, 1990).

Ethical considerations

The project was reported to and approved by the Norwegian ethical committee (NSD), before the start of the data collection. Before the participants started the interview they were informed about their rights and terms of participation. They were told they could stop at any time, did not have to answer questions they did not want to, and that the interview was confidential. The participants were asked to orally consent to these terms of participation, and only then could the interview start. The two people who had access to the non-anonymised recordings of the interview were my supervisor and I. We were also both present during the interviews.

Moreover, during the coding and reporting of the data no information will be given that could be traced back to the original source. Here by ensuring the anonymity of the participants of the study. Therefore, no references will be made to the gender, age, or occupation of the participant.

Furthermore, all recordings of the interviews, audio recordings, transcriptions, and notes, will be destroyed once the project is finished.

Results

This section will first present the context, where after the results are presented as categories in accordance to grounded theory, and visualised as a model. To illustrate how the categories are grounded in the data collected, a table with quotes is presented (see table 1 and 2).

Context

The context is the background from which the interviewees respond to in actions and emotions (Corbin & Strauss, 2008). In order to provide a framework for these actions and emotions the local context of this study will be presented. The context will be described based on three categories: the technology, the work environment and organisations, and the end-users. The information presented in the context categories originates from the data gathered in the interviews. Hereafter the results will be presented as categories in accordance to grounded theory, and visualised as a model. To illustrate how these categories are grounded in the data collected, a table with quotes is presented.

The technology. The technology that was to be developed needed to enable the drilling of wells that were not accessible with conventional drilling equipment. The conventional drilling equipment relied on manual usage, whereas the technology that was to be developed would be automated. The designers had to look for a drilling solution that was suitable for the circumstances.

The work environment and organisations involved. For the design and development of this new technology the customer hired designers from several companies. The customer recruited one main contractor; who was made responsible for designing the new technology. Since the technology was so complex several subcontractors were also hired to develop individual parts of the technology. The main contractor and the sub-contractors that were hired by the customer had regular meetings. The project leaders of these companies met in these meetings with the project leader of the customer company. Here they discussed the development of the design, presented progress, and performed risk analyses. Sometimes experts were brought into these meetings to contribute to a specific topic, for example risk analysis.

With exception of these meetings the designers worked relatively independently. Often they also had teams within their own company working on the development of the new technology.

For this study people from the project working for the customer company, main contractor company, and subcontracting company that developed a model, were interviewed.

The end-users. The end-users of the developed drilling equipment based on new technology are the people working offshore on a drilling rig. The educational background of the end-users ranges from plumber to a university degree as an engineer. They have a very typical work culture offshore due to the special working conditions. The end-users typically work on a two weeks offshore, 4 weeks onshore basis, and at the platform they work in an enclosed 24-hour society where they work 12-hour shifts, one-week day shifts and one-week night shifts. Furthermore, the work environment is limited in space and very noisy, dirty, and part of a high-risk industry. Within this industry it is normal that the contracts for certain services are taken over by other companies. So for example the drilling contract could be taken over by another company after a few years. This was described by one of the interviewees as usually just a change of the shell and not the actual crew. Nonetheless, every company has slight differences in their approach.

The end-users can be divided into different categories, namely the drillers, the drilling crew, and the operators. Furthermore, the end-users working with this new technology work (on paper) for different companies, which increases the complexity of the situation. Nevertheless, when operating the new drilling equipment it is very important that they work well together and have a clear communication. Especially when the people that need to work together are at separate locations on the offshore platform. There is also a very strict hierarchy offshore that is respected by the end-users.

What is more, the designers often described the end-users, at first, as being conservative and highly reluctant to change. However, after some interaction with them the designers admitted to be surprised by the inquisitive attitude of the end-users.

Categories found in the study

The core category found in this study was the understanding of the end-users' competencies. The relation between the main categories and the core category can be defined as how the understanding of the end-users' competencies is expressed. The main categories are: training of the end-user, proximity to the end-user, experience transfer from previous projects, automation vs. human action, and learning from tests.

The variables that are affected by the understanding of the end-users competence are all aspects of the end product, the new drilling technology. These are called outcome variables, and there are four of them: user-friendliness of the product, perceived safety of the product, complexity of the product, and cost of the product. Table 1 and figure 2 show the categories and some example quotes that ground the categories in the data. These categories will be further explained in the sections below.

Core category: Understanding of the end-users' competencies. The core category that emerged from the data was the designers' understanding of the competencies of the end-users. The drillers, the drilling crew, and the operators needed to work directly with the new drilling equipment. The core category reflected how the designers understood their competencies. In reality the background of the end-users ranged from plumber to engineer. The successfulness of the design depended, amongst other things, on how well the designers understood who the end-users were and what their competencies were. Newly designed equipment that is not well adapted to the existing competencies has consequences for the economics of the project as well as the safety of the end-result.

Furthermore, what emerged from the data during the analysis was that this understanding of the end-users' competencies differed for the three types of actors involved in the design of the technology; the customer, main contractor, and sub-contractor. The subcontracting company indicated that they were very unaccustomed to operational projects like the one of developing this new equipment. They said that usually they were more involved with research projects, and that they do not have routines for developing commercial products. Therefore, they had less experience with user-centred design, and minimal experience with the end-users. This led to a mismatch in the sub-contractor's understanding of the end-users' competencies.

The understanding of the competencies of the end-users can be broken down in three concepts: understanding, competencies, and end-users. The topics that were discussed during the interviews could almost always be led back to one of these three topics, or a combination of them. They were expressed in five ways, as can be seen in table 1; the need for training, the experience transfer from previous projects onto this project, how close the designers were to the end-users, how well they learned from the tests, and the attitude towards human error. These main categories will be further explained in the sections below. Furthermore, the consequences of the understanding of the end-users' competencies for the product will be discussed with illustration of the main outcome categories: user-friendliness, complexity, and the perceived safety of the product.

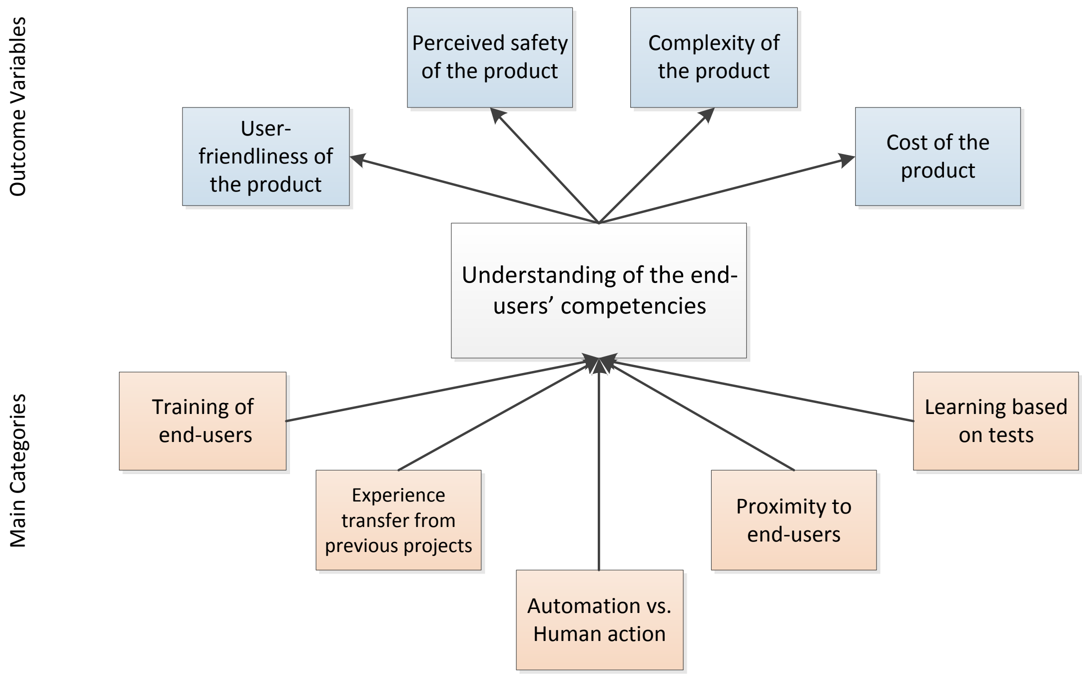

Figure 2. Understanding of the end-users' competencies model

Main Categories	Quote
Training of end-user The need for training is recognition that the competency level of the end-user needs to be developed. For this technology training was deemed important, however, the end-users did not **ha**ve all the means to train.	*You have to have the whole crew in [technology]-modus. I think that the next time we will do an operation that we need to include larger parts of the drilling crew in the training.* *Yes we noticed quickly that there was much variation from person to person, but some became very unsure about what they should do. And they have their usual driller's first action that when something happens you do this and that. But with [the new technology] it might be completely wrong to do that. It messes with people's intuitive reaction.* *There is a lot of focus on that (communication), especially before the first operation. There was a lot of focus on this and there were big meetings and teambuildings and joint training in a simulator and such with [the subcontractor] and the whole rig crew.*
Proximity to the end-user The proximity of the designer to the end-users. Proximity is interpreted in this category how well the designer understands the end-user, how close are they.	*(about the inclusion of the end-user) It was a conscious strategy, because those who will operate the equipment are the ones with the best competencies on how things will work in practice.* *(from one of the interviewees from the subcontracting company) In the first phase, before we started drilling the first well we did not know them (the end-users). We had an understanding of what drilling includes and such, but after we had been offshore for the first well we learned a lot about the situation and how they (the end-users) work.*
Experience transfer from previous projects Experience was transferred from the first project to the second without consideration of the difference in competency level of the end-users and the accompanying consequences.	*I have to say that I see a bit of a difference between the questions we get and forums that we attend and have meetings on and stuff, and maybe there is a bit higher competency level at [first platform] than on [current platform].*
Automation vs. Human action The attitude the designer has towards human error determines the way he or she will approach safety. Human action is seen by the designer as a necessary evil, therefore the designer will try to avoid human action and thereby in their view human error.	*…some of the point is that if we can avoid that things have to be solved by human action then it is often safer.* *…. and again, it requires that the competency level of the people we send out has to change. They have to be able to handle this type of systems.*
Learning based on tests The adjustments that were made to the technology based on observations, analyses, or test results. The dynamic process of designing a new technology offers the opportunity to experience a learning curve. For the subcontractor this learning curve was probably steepest.	*…there were 88 points that had to change in the procedures that we could not do as we had thought. So we had to try it, because when you test things in reality things are very different from on paper.*

Table 1. The main categories, their explanation, and illustrative quotes.

Main category: Training of end-user. Analyses showed varying views on training of the end-users by the interviewees. Everyone agreed that the end-users should receive some form of training, however the opinions differed on how well this was done and how much training they needed. Training was also the area where most interviewees indicated there were some challenges within the project. The indicated need for training is a reflection of the way the designers perceived the competency level of the end-users, and where they believe the greatest challenges of the human-technology interaction, and human-human interaction lie.

The contractor indicated that they had very stable training routines for their crew, and that they tried to include the rest of the personnel as much as possible within training procedures for the new technology. The contractor also admitted to having experienced some problems with the subcontractor training the contractor's crew in the part of the technology that the subcontractor developed.

Furthermore, some interviewees recognised the importance of training, because some of the features of the new automated technology are counter-intuitive compared to the manual technology they previously used. Also, the cooperation and communication between the two teams that are primarily involved in operating the new technology, is stressed as being important and should be trained intensively.

Main category: Experience transfer from previous projects. The new technology has been implemented on different petroleum producing installations. On the first installation the competencies of the end-users were different from the competencies of end-users in the current study. The general competency level at the first installation was described as being higher than on the one at hand in this study.

Nonetheless, the experience from the first project was transferred to this project with seemingly little consideration of that difference in competency level. The implementation phase on the first platform was described as smoother than on this platform, where problems with the user-friendliness of the technology kept reoccurring.

Main category: Automation vs. human action. Avoiding human action was seen as safer, and almost all interviewees generally preferred automation. So in order to reduce human error more automation was needed. However, this view on human action (and thereby competencies of the end-users) and the resulting increased automation has consequences for the tasks of the end-user. Their tasks change; less people are needed to operate more automated technologies, but the number of systems to watch increases. Moreover, the systems and technologies increase in complexity, which requires a different set of competencies to operate these systems.

Main category: Proximity to end-user. The main category proximity concerns the distance between the designer and the end-user. How well can the designers relate to the working conditions of the end-users and to the end-users themselves? The distance between the two is often reduced by experience of working together, and inclusion of the end-users in the design processes (from the beginning). The inclusion of the end-user was very important for the customer, and throughout the design process different end-users were invited to join risk analyses and reviews of the design. Interviewees from the subcontracting company expressed that they learned a lot about the rig and well operation after the training period, two months before the first operation using the new technology. However, prior to that encounter they admitted to not having a good understanding of who the end-users really were. Their understanding was mainly based on stereotypes.

Main category: Learning based on tests. A designing process is a dynamic process. The different stages of the design process are re-evaluated based on new information or outcomes from analyses and tests. In the process of developing this new drilling technology the designers, especially those from the subcontracting company, developed their understanding of the competencies of the end-users. They observed, mainly during the testing and implementation phases offshore, who the end-users really were, what worked, and, most importantly, what did not work. Based on these observations adjustments were made. These adjustments, or attempts to adjust the technology to better suit the needs of the end-user, demonstrate learning.

Outcome categories

In figure 2 an outcome category was included, namely the product. This category will be presented as an outcome of the designers' understanding of the competencies of the end-users. The product of the design project is the developed technology, and here it will be discussed how the understanding of the competencies of the end-users have influenced the outcome of the design. The categories that emerged from the data describing the characteristics of the final product were the user-friendliness of the product, the complexity of the product, the perceived safety of the product, and the cost of the product.

Main Outcome Categories	Quote
User-friendliness of the product User-friendliness refers to ease with which the end-user is able to use the new technology. This implies that the technology should be intuitive, and adapted to the competence level of the end-user. However, some parts of the technology were not well adapted to the competencies of the end-user.	*…and we had to develop a commercial user interface that they had to use. There were no strict limits other than that it should be commercial and user-friendly.* *There are absolutely challenges with using this [sub-contractor] model. It has a complex HMI.* *…but that it should be intuitive was a bit difficult, that was maybe not that we did best because the model requires things to be in a special way. A part of the data that is to be entered is something that people do not have a special relation to, it is detailed lab data […] for example, and there are very few people that understand how it should be. Some of the challenges here are that we who worked at (subcontractor) we know quite well what it is we need and how it should look, but when you then train a (contractor) who might come straight from technical school or something like that, they have slightly different assumptions both for usage and understanding what is right and what is wrong.*
Perceived safety of the product The view on safety is mainly expressed in terms of risk analyses and testing. The customer had made safety a priority and this was clearly expressed by the main and sub-contractor as well. Overall, the technology was deemed to be safe in spite of problems with user-friendliness and training.	*(about safety)…the way we find out about that is via HAZOP functions or HAZIDs.* *(about measuring safety)…you are measuring safety, or you are measuring the amount of accidents over time. And if the frequency is higher than this and this number than we have to find a reducing measure.* *Both in international law, [national law] and [the standard]. The [standard] is the official demand we have to meet, but we have much stricter demands than what it says in [the standard].* *Haha…the cost. It was expensive, it was an expensive undertaking, but I believe that safety-wise and design-wise we did a lot of things right.*
Complexity of the product The product is considered to be complex due to the amount of equipment necessary to use the technology, the complex HMI of the model, and the involvement of several actors during the operation phase.	*There is a lot of interest and use for this technology, but it is a bit difficult to start using it. Because it demands more equipment and new equipment, which has not been used before and this is a bit of a conservative business.*
Cost of the product The design project was very costly. However, the alternations that are still deemed necessary will further increase the total cost.	*And [subcontracting company's personnel] is expensive to use, so it is not desirable to have them out there.* *They have invested a lot of money in that (model), when it comes to development and testing and modifying of the model.* *But at the end of the day [the customer] has invested a lot of money in the [subcontractor's] model and it would be good to get to the point where that was a commercially available package that, you know, engineers throughout [customer's company] could be trained upon.*

Table 2. The outcome categories, their explanation, and illustrative quotes.

Main outcome category: User-friendliness of the product. One of the objectives of the design project was that the new technology should be user-friendly. However, in order to make a technology user-friendly knowledge of the end-user is required. A recurring topic whilst talking about the new technology with the interviewees was the challenges with the user-friendliness of the model of the subcontractor. They themselves indicated that the objective of their work was that the model should be user-friendly and commercial.

It seemed that there was a mismatch between the end-users' actual competence and wishes, and the designers' understanding of the end users' need to make the technology user-friendly. The challenges with the user-friendliness of the model were assigned to the complex Human Machine Interface (HMI) of the model. The contractor had proposed to the customer that the next upgrade of the model should focus on user-friendliness.

Main outcome category: Complexity of the product. The final product has a high level of complexity. In order to operate the technology a lot of equipment is needed and needs to be mobilised. In addition to this large amount of equipment that is needed, several of the different parts of the equipment are owned by different companies, which need to be present to operate their own parts as well as to cooperate and communicate with the other parties involved under the complex drilling operations. Even though this situation is not unusual in the offshore working environment, it contributed to the high-complexity level of the drilling operation (using this new technology). Moreover, the HMI that is behind the computer model used to steer the operation is also very complex. The HMI has been described earlier as not user-friendly.

Overall, the product is evaluated as being complex and it is debated if the competency level of the end-users is high enough to safely operate the complex technology.

Main outcome category: Costs of the product. An additional consequence of the product and the understanding of the end-users' competencies are the costs that are associated with the project. The project was already an expensive endeavour and safety was said to be prioritized over cost pressures. However, due to complications with the understanding of the end-users' competencies, modifications will have to be made to the HMI of the model to increase the user-friendliness of the design. These modifications will have serious consequences for the budget. Additional costs will have to be included in the total costs of this design project. Spending more money on the modifications of the model will mean that there is less money to spend on other project areas.

Main outcome category: Perceived safety of the product. From the interview data a view on safety emerges, as can be seen in figure 2. Here it was found that risk analysis was used not only to measure safety, but also to express safety. In the risk analysis the risks in the design are analysed, and the barriers that are present are evaluated to judge if they can counterbalance the found risks. If this is not the case, then (based on the results from the risk analyses) appropriate barriers, either, software, hardware, procedural, or a combination of the three, are implemented into the design. The safety of the design is further expressed by the results from several testing phases. If the tests run without any problems, then this is additional proof for the designers that the design is safe. The focus in the assessment of the safety of the design is technical. The interviewees indicated that human factors specialists were called in for certain analyses. The focus whilst talking about safety remained more technical than operational.

Safety was described as a priority within this project. The designers said that they were working with standards that were even stricter than required by either national or international law. The overall conclusion of the interviewees was that the technology is safe to use at the moment, despite that, they express worries about the user-friendliness of the model and the training opportunities for the end-users. The training opportunities with the technology are restricted due to limited drilling operations and the lack of a simulator at the moment. These challenges compromise the overall safety of the technology. From a technical perspective the technology appears to do what it is supposed to do; nonetheless it was made by people and has to be operated by people, and thereby it is subject to human error. The overall safety the technology is a combination of the technical safety and the operational safety. The latter is dependent on human factors, such as the competencies of the end-users. It is therefore of the utmost importance that the people that design technologies have a correct understanding of what those competencies are.

Discussion

The analyses of the data showed that safety or a safe product is about more than merely following the rules and laws imposed on the design and design process. The core category that arose from the data in this study concerned the importance of understanding the end-users' competencies in relation to the safety of the product. The understanding of the end-users' competencies was based on the training of end-user, the experience transferred from previous projects onto this project, the attitude towards human action vs. automation, the proximity to the end-users, and learning based on the tests run on the new technology. They serve as indicators of the level of that understanding.

The level of understanding of the end-users' competencies was not the same for all companies that were interviewed; some had a more accurate understanding than others. These differences in understanding were caused by differences in the five main underlying categories previously mentioned.

Moreover, the differences in the level of understanding of the end-users' competencies had consequences for the final product. These consequences were prominent in four outcome indicators: user-friendliness, complexity, costs, and perceived safety. The product showed a high complexity with a low user-friendliness. Nevertheless, the product is viewed and evaluated, through risk analyses, as being safe. As a consequence of the difficulties with the technology the costs of the project have been very high and are still increasing.

Answering the initial research question (*Which factors influence the development of a safe design?*) based on the data analyses is difficult. There have been several aspects of this design and design process that have contributed to the safety of the product. However, I would describe the core category that emerged from the data, the understanding of the end-users' competencies, as the main factor that influenced the safety of the design in this study. The prerequisite for a safe design is for the designers to understand the end-users' competencies. This would require the designers to involve the end-users in an early design stage and familiarise themselves with the end-users' working environment. This increases the proximity between the end-users and designers. Additionally, this will help to judge whether the experiences from other projects can be transferred directly, or should be adapted to the competency level of the current end-users. Furthermore, these insights into their competency levels make it easier to decide which parts of the technology that should be automated and which parts can be dealt with by human action. Consequently, the training would be adjusted better and more appropriate. Finally, the test results that reflect the end-users' competency level should lead to changes being made in the design.

These actions can have an effect on the outcome product: the drilling technology. With an increased understanding of the end-users' competencies the technology would be likely to be more user-friendly, less complex, less costly, and safer. It would be more user-friendly and less complex due to the better adapted user-interfaces based on the understanding the designers would have of the end-users competencies, safer because the technology would be more intuitive to use and this would decrease the chances of human error, and less costly because there would be no need for changes in the design in later phases of the design process.

The model would thereby predict that optimizing the input variables of the core category would increase the understanding of the end-users' competencies and as a consequence increase the user-friendliness and safety, and reduce the cost of the project and the complexity of the technology. To determine whether the model is complete is a challenging task, and I would recommend this to be done with a quantitative study using for example structural equation modelling.

The factors that have been identified in the analysis are, however, not completely new according to other theories concerning human factors in design. In software design there has been a much more rigorous focus on user-centred engineering (e.g., Nielson, 1993). This user-centred design has four approaches to design:

- Early focus on the users and tasks
- Performing empirical studies such as usability tests and questionnaires focusing on quantitative data
- Iterative design using prototyping, allowing for quick changes based on feedback from the users
- Participatory design were users are part of the design team

These approaches would have allowed for the designers involved in the current study to learn from tests, get closer to the end-users, put the experience from the previous project in a better informed context, know what new aspects could be trained for, and give a better informed input into their decision for human action or automation.

The goal of any human factors specialist within a design team would be to develop a design that supports the needs of the end-users instead of developing a design that the end-users would have to adapt to. Even though humans are flexible and capable of learning, technologies would be safer, less complex, user-friendlier if they were designed based on the needs and competencies of the end-users. Such awareness is present amongst the designers of software, however is not yet installed in the oil and gas industry.

These findings are congruent with existing theories on design. It appears the designers in this project did not fully understand whom they were designing for. This lack of human factors in design is common (Wickens, et al., 2004). The fact that end-users were barely involved in the design process and as a consequence, that their competencies were not fully understood, showed in the outcome categories. Theories on human factors in design emphasise that design was previously more technology driven and had characteristics of reactive design. In the future designers should let human factors drive design and opt for a proactive design approach, as proposed by

Karwowski (2007). This is similar to resilience engineering (Hollnagel, Woods, & Leveson, 2006), which also claims to focus more on the flexibility of the system, namely the technology in interaction with the humans operating it.

All interviewees mentioned that there was a lot of focus on safety during the design process. The perceived safety of the developed technology was high. Nevertheless, the interviewees themselves indicated that there were problems with the complexity and user-friendliness of the model. I would therefore like to derive that there was a high focus on technical safety, on the reliability of the technology. However, they seem to have less consideration for operational safety. This lack of awareness of operational safety is not unexpected. During the design phase a lot of the focus is given to the actual technology, and less on the people who will use the technology in the future. This is evident from the many different types of risk analyses that were performed in the duration of the design process. These types of risk analyses traditionally have a higher focus on technical safety than on operational safety.

However, it is evident that the high complexity of a technology and lacking user-friendliness increase the likelihood of human errors (Hollnagel, Woods, & Leveson, 2006). Higher awareness of human factors during the early design phases of developing a new technology could increase the designer's understanding of the end-users' competencies and thereby aid the development of a safer and more economic design.

Validity of the qualitative analysis

In order to evaluate the value of a study the terms validity, reliability, and objectivity are usually discussed. However, for qualitative studies these terms are not very applicable due to the methodological differences between quantitative and qualitative studies (Yardley, 2000). Yardley (2000) proposes to evaluate qualitative studies based on the sensitivity to context, the commitment and rigor of the researcher, the transparency and coherence, and the impact and importance of the study.

The data has been analysed in the context of the study. The context has been described in the result section and the interpretation of the model should be made in light of this context. Even though some findings might be transferable to other cases they should never be taken out of context.

The commitment and the rigor of the study have been assured by the structural use of grounded theory and the iterative processes that lie underneath the methodology. This method was used to produce a model; this model is supported not only by the structural use of the method, but is also made transparent by the documentation of the method as well as by the use of illustrative quotes that support the model. The categorisations and interpretations have been made by closely following the guidelines stipulated by grounded theory (Strauss & Corbin, 1990). Moreover, any deviations from this approach have been explained and discussed in sections above. The transparency of the study was further promoted by informing the interviewees that they could and should speak freely, that their data would be anonymised, and that only my supervisor and I would have access to it.

The study shows coherency by letting the research question determine the method and subjects of the analyses. The research question lent itself for the choice of the grounded theory method and since the research question focused on safety in design of new technologies only designers of new technologies were interviewed.

Limitations of the study

A limitation of the validity of this study is that the data is gathered in retrospect. The interviewees were talking about their experiences of developing the new technology after the fact; we were not able to follow the process as it went on. The study is therefor reliant on the quality of the retrieved memories of the interviewees. Previous studies have proven that memories might be incomplete and or biased (Anderson, Bjork & Bjork, 1994; Kahneman, Tversky & Slovic, 1982).

Furthermore, another limitation to this study was that the interviews were generally conducted in Norwegian, which is not my mother tongue. This could cause misunderstandings during the analysis of the data or cause the loss of information. However, my supervisors are native Norwegian speakers and one of them was a second analyst during this study.

An additional limitation of the study was not being able to go back to the interviewees. In accordance with grounded theory the researcher should be able to go back to the interviewees to ask additional questions based on new questions that arise from analyses. Unfortunately, due to our specific sample this was not possible. Nonetheless, the interview guide was evaluated after every interview to accommodate new insights and to include new questions and themes. Moreover, several designers working for the same companies were interviewed so that we could verify information or ask new questions that were related to the role of the company during the development of the new technology.

The data that was gathered for this study could have been interpreted and categorised in a different way. There is a subjective quality to the study, regardless of the intentions of the researcher to remain as objective as possible. Nonetheless, the results are to be judged as valid. During the analyses there was a second analyst conducting a grounded theory study, independently, based on the same data. This second analyst, my second supervisor, came to similar conclusions.

Future research

The categories found in this study could be used to develop a questionnaire. This could help further quantify the importance of the factors found to influence a safe design. Additionally, it would be interesting to further explore other design projects to identify factors that are stable across different types of projects. In that same vein it would be fascinating to see if these factors are similar cross-culturally. In this globalised world where design projects are often international it would be interesting to research if culture influences what is viewed as safe design.

Human factors in design are often poorly analysed (Woods & Dekker, 2000). This study shows the need for such analyses. According to Woods and Dekker (2000) the analyses that are performed are often taking shortcuts and do little justice to the importance of human factors in design. There is a need for studies that are able to analyse the complexity of the interaction between humans and machines. Woods and Dekker (2000) have proposed scenario-based analyses as a solution for the analysis of human factors and technological change. Further research should look into further developing these ideas into workable analyses with an emphasis on the designer understanding the competencies of the end-users.

Implications of the study

The study found that the understanding of the end-users' competencies has a strong impact on the safety of the developed technology and the overall operational safety of the organisation. A misunderstanding or lack of understanding of those competencies will also lead to a more complex, less user-friendly technology, and a higher cost of the design project. These findings stress that a better understanding should be reached in an early stage of the design process and that user-centred design is essential for safe design (Norman & Draper, 1986; Maguire, 2001). In accordance with existing theories these results further stress the importance for safe design.

The underlying factors that influence the understanding of the competencies of the end-user are new to this study. These factors: training of the end-users, proximity to the end-users, experience transfer from previous projects, learning from tests, and the attitude towards automation vs. human action, led, in this case, to an insufficient understanding of those competencies by all parties. However, these factors have the potential to be optimised, thereby improving the way the designers understand the competencies of the end-users. This knowledge could lead to a higher focus on these factors in future design projects and as a result increase the designers' understanding of the end-users, and in the end contribute to a safer design.

Conclusion

Safety is usually seen as a combination of operational safety and technical (design) safety. However, this study has shown that the interaction between humans and the technology is critical to the safety of the design. Therefore it is not possible to solely base safe design on technical features, latent failures are not just technical. A more holistic approach to safety is necessary when judging the safety of design, and the designer's understanding of the competencies of the end-users is central to that. Hopefully these findings will help raise awareness amongst designers working in high-risk industries for more and an earlier focus of human factors in design, and contribute to safer designs.

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