Int. J. Engng Ed. Vol. 19, No. 1, pp. 192–205, 2003
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Drift and Vulnerability in a Complex Technical System: Reliability of Condition Monitoring Systems in North Sea Offshore Helicopter Transport*

G. WACKERS
Maastricht University, Department of Technology and Society Studies, P.O. Box 616, NL-6200 MD Maastricht, The Netherlands. E-mail: g.wackers@tss.unimaas.nl

J. KØRTE
Helikopter Service AS and Stavanger University College, P.O. Box N-4055 Stavanger Airport, Norway. E-mail: jens.korte@tn.his.no

In the early 1990s vibration-based condition monitoring systems called Health and Usage Monitoring Systems (HUMS) were introduced into the helicopter industry servicing offshore operations in the North Sea. These monitoring systems were specifically designed to improve the helicopters' safety, reliability and availability by providing in-flight, early warning diagnostics; they were reliability technologies that would simultaneously reduce maintenance costs. On September 8, 1997, LN-OPG, a Super Puma helicopter operated by the Norwegian helicopter operating company Helikopter Service AS, was involved in a fatal accident due to a mechanical failure in the engine and gearbox driving shafts. The helicopter was equipped with a HUMS-system that should have detected the impending failure, but failed to do so. This paper tries to understand why HUMS failed in its early warning capability in LN-OPG. It raises practical issues to adopt in one's own working environment in realising system designs that will anticipate, cope with, resist, and recover from vulnerability and failure caused by component or procedural drift over time.

INTRODUCTION

THE DESIGN and implementation of modifications of complex technical systems requires a redesign of the organisations that operate and maintain them. Furthermore, the design process should also consider how to cope with the *drift* that the heterogeneous system of the technology and its maintenance organisation might undergo *over time*, producing vulnerability, that is, a diminishing system capacity to anticipate, cope with, resist, and recover from the impact of a critical degradation failure. This paper raises these issues through the examination of a concrete case in which drift was not, or only insufficiently, considered.

In the early years of the 1990s, helicopters servicing the offshore industry in the North Sea were equipped with vibration-based condition monitoring systems. These Health and Usage Monitoring Systems (HUMS) were introduced with the aim to make helicopter transport safer. However, in practice the implementation and operation of HUMS systems turned out to be troublesome and frustrating.

On September 8, 1997, a HUMS-equipped AS 332L1 Super Puma helicopter, operated by Helikopter Service A.S. (HS), crashed into the sea on its way to a floating production vessel at the Norne field, approximately 200 km west of the Norwegian coast. None of the 12 people on board survived the sudden accident [1]. (Helikopter Service A.S. is the largest offshore helicopter operating company in Norway. During the time period covered in this paper it underwent several changes. It acquired some of its smaller Norwegian competitors and was itself acquired by Canadian-based CHC Helicopter Corporation. In 2000 the Stavanger-based company was divided into two separate companies: CHC Helikopter Service, comprising the helicopter operations and training centre, and Astec Helicopter Services, now an independent helicopter support, repair and overhaul company. In this paper we are using the name Helikopter Service A.S., or HS, to refer to the company's structure around 1997, in which operating, maintenance and repair functions were integrated within one company.) Using a detailed account of this helicopter accident and its context as a 'point of entry' to and a 'strategic research site' on the subject matter, this paper examines the complex transformations that the introduction of HUMS in the industry produced in the maintenance organisation of Helikopter Service A.S. (A 'strategic research site' is an important methodological notion in the field of science and

---

* Accepted 12 September 2002.

technology studies. It urges the researcher to think carefully about where to conduct his or her research. It is important to find places where extant knowledge systems, technological arrangements and solutions are being tested, questioned and interrogated. Accident sites are such places [2].)

More specifically, the paper will examine the formation of new HUMS-related maintenance and operating routines in a context in which the company's maintenance organisation is struggling to make sense of the system's (unreliable) output. We will then turn to the question of how and why the system failed to detect the impending failure that resulted in the death of 12 people and the complete destruction and loss of a helicopter. The account of the accident reveals a gap between 'practice' on one hand and rational representations of policy goals, decision-making processes and technical design features on the other; and a 'drift' along a 'regularity gradient' from optimal technological capabilities towards a more vulnerable state.

THE 1997 SUPER PUMA HELICOPTER ACCIDENT (NORNE) AND ITS CONTEXT

Loss of the helicopter, search and recovery

In the early hours of September 8, 1997, 10 people boarded a Super Puma helicopter at Helikopter Service's base in Brønnoysund. With a crew of two pilots, the helicopter departed for an approximately 200 km long flight to a large ship-like floating production, storage and offloading vessel (FPSO) at the Norne field.

Around 6.55 hrs the pilots signed off with the air traffic controllers at Bodø airport and, with 11 minutes flying time left, they announced their approach one minute ahead of schedule to a drilling rig in the vicinity of the Norne ship. When the helicopter had not arrived by 07.20 hrs the crew on the Norne ship realised that something had gone wrong, although no Mayday call had been received. Land stations were alerted and an emergency search and rescue operation was initiated. Confirmation of the accident came when at 13.22 hrs two bodies and helicopter debris (an empty rescue vessel and an undamaged rotor blade) were found.

Throughout the day of the accident and the following day the search for the exact location of the helicopter wreck continued. The wreck was located late Thursday night, September 11. The helicopter was ripped apart into a nose, cabin and tail section. In lifting the wreck, priority was given to the tail section containing the records of the combined cockpit voice and flight data recorder (CVFDR) in the crash-resistant proverbial 'black (but actually orange) box'. Hampered by bad weather conditions, the cabin section, with the engines mounted on its roof, was recovered a couple of days later. Gross visual inspection revealed that one of the engines was heavily damaged. Furthermore, some of the bodies recovered from the wreck had burn injuries, suggesting that there had been a short burst of fire. On the CVR-tape there was a recording of one of the pilots mentioning a light of the engine overspeed protection system coming on, just before the recording was abruptly cut off.

Context of the accident

The Norne ship was in the process of being completed. Norne had a history of problems. The hull was being built for the Norwegian oil company *Statoil* in Singapore. The quality of the work was so bad, however, that Statoil management decided to bring the ship to a Norwegian shipyard, *Aker Stord.* Faults were discovered in many of the titan weldings. It was estimated that repair work would require 200,000 man-hours, but turned out to amount to 700,000 man-hours. Instead of finishing the installation work near shore, the ship was towed to the Norne field where it arrived on July 21, 1997. A two-week strike, supported by an oil workers labour union, produced more delays. Due to these delays Statoil was under pressure to get the platform finished before the scheduled start of production on October 1, 1997. Meeting this goal required the deployment of several workers in excess of the ship's accommodation capacity. Those had to be shuttled from the ship to Brønnøysund and back on a daily basis. For this kind of commuting Statoil should have submitted a request for approval to the *Norwegian Petroleum Directorate*, but failed to do so. Labour unions claimed that oil companies prioritised profitability higher than safety and demanded a thorough investigation of the consequences of safety/profitability trade-offs in North Sea helicopter transport. Statoil apologised for the transgression of regulations, rejected the general criticism, but cancelled the shuttling of workers to the Norne field the day after the accident.

Statoil recognised that helicopter-operating companies had not been immune to the increased emphasis the oil industry put on cost reduction, which combined with an increase in traffic. Oil companies' actual helicopter traffic needs turned out to be higher than what they had offered as prognostic estimates to the helicopter operators. Being one of HS' largest customers, taking up approximately 50% of the company's capacity, Statoil admitted to being to blame for that. HS struggled with the procurement of a sufficient number of helicopters and with the recruitment of qualified helicopter pilots. According to Statoil, these conditions imposed a strain on personnel at HS, and on the helicopters an exploitation level that bordered on what was justifiable [3].

Among those who in their comments to the media emphasised the improved safety of offshore helicopter transport were *SINTEF* researchers. They were involved in work on a (second) major helicopter safety study that was about to conclude to an approximately 50% reduction in the average risk from period 1 (1966–90) to period 2 (1990–1998). From 1990 to 1998 alone the reduction in risk was estimated to be 12 %, with the implementation of HUMS topping the list of main contributing factors [4].

Immediate causes

Prior to the recovery of the cabin section of the wreck, theories concerning the immediate or technical causes of the accident centred on the main rotor system. A detached rotor blade had been found among the debris that confirmed the accident. The undamaged condition of the rotor blade suggested the unlikely event that the blade might have detached during flight. Furthermore, a mechanical failure in the main—non-redundant—rotor system would explain the suddenness of the accident. When the main rotor systems fails there is no back-up system to replace its function. On the basis of these findings, HS management made the decision to ground the other four Super Puma helicopters of that particular type (AS332L1) because they were equipped with identical main rotor systems. Two days later, on Friday, HS' grounding decision was followed up by a directive from the Norwegian civil aviation authority to ground all AS332L and L1 Super Puma helicopters. Helicopters of the type AS332L2 were exempted from this decision due to the fact that their rotor drive system was of a new generation design. Although reluctantly, in subsequent days the grounding policy generalised to include all types of Super Puma helicopters, causing severe disruptions in the regularity of helicopter transport to and among production installations in southern parts of the North Sea.

Prior to the actual recovery of the engines it was considered unlikely that the accident was caused by a sudden failure of the engines. Like all helicopters used in North Sea offshore transportation, the helicopter was equipped with two engines (technical redundancy) mounted on the roof of the helicopter fuselage. Both engines were linked up with the main gearbox that translated the 22,840 rounds per minute of the engine shafts into the much slower rotation of 265 r.p.m. of the single main rotor of the helicopter. Each of the engines is powerful enough to fly the helicopter. Although constituting an emergency situation, the simultaneous shutdown of both engines does not mean that the main rotor stops. The air passing through the rotor as a result of forward and downward speed would keep the rotor turning (windmill effect) allowing the pilots a controlled emergency landing (at sea or on the deck of a ship or nearby offshore platform), as long as the control lines from the cockpit to the rotor are intact. A so-called 'auto-rotation' is a standard emergency landing procedure trained for by helicopter pilots. This would also allow time to send a Mayday call.

However, the technical investigation conducted after the recovery of the engines identified a mechanical fatigue failure in one of the engines as the immediate cause of the accident. The engine shaft and the main gearbox shaft engage in a key and keyway arrangement. The engine's driving shaft consists of a thin-walled, hollow cylindrical structure (Bendix shaft), a couple of inches in diameter. Bolted to one end of this driving shaft is a splined flange, a cylindrical, 'female' receptacle (keyway) that receives and engages with the 'male' part (key) that is bolted onto the shaft of the main gearbox. This part is called the *splined sleeve*. The splined sleeve cracked and fell apart, releasing a part called the lock washer that was designed to 'lock' the sleeve's bolt into place. The lock washer and fragments from the splined sleeve entered into the lumen of the Bendix shaft. The enormous centrifugal forces generated in this driving shaft, rotating with a speed of 22,840 r.p.m., slammed the lock washer against the thin wall of the Bendix shaft and ripped it apart. Loosing its load the engine shaft's rotating speed increased immediately, activating the engine *overspeed protection system* (warning light in cockpit coming on). However, the imbalance in the Bendix shaft immediately destroyed the sensors designed to pick up changes in rotational speed, deactivating the overspeed protection system. Debris from the damaged engine penetrated the heat shield between the two engines, destroying also the other engine. Debris also penetrated the roof of the helicopter fuselage and destroyed the control lines from the cockpit to the main rotor, thereby denying the pilots any possibility to control the aircraft and perform an emergency landing by 'auto-rotation'.

Unserviceable HUMS sensor

Two more pieces of information are important. Health and Usage Monitoring Systems (HUMS) are a kind of external sensory nervous system with sensors sprawling out over the safety critical parts of the helicopter—the power train consisting of engines, gearboxes and rotors—designed to capture changes in vibration patterns that might indicate imminent failures. The company's internal investigation conducted by HS immediately after the accident revealed two things. First, one of the HUMS sensors on the main gearbox housing (the one that later turned out to be the one located exactly over the splined sleeve that failed) was defect. It had been unserviceable for two months. Second, HUMS engineers in Stavanger discovered in the HUMS data batches from previous flights, that were stored in the ground station computer in Brønnøysund, a trend in one of the parameters. The trend originated in one of the sensors on one of the engines. This particular trend could only be found through manual retrieval and examination of the data. This was not done routinely. Normal use of the HUMS system relied on the production of automatically generated alerts. At first, Helikopter Service engineers did not attribute much significance to this discovery due to the unlikelihood of a failure of the engines and the focus on a failure of the rotor blade attachments. When the severely damaged engines were recovered the discovery of the trend came into full focus. The proximity of the sensor that picked up or generated the trend to the one that was unserviceable suggested that the sensor that was defect, had it been serviceable, could have picked up the trend too. This opened the possibility that it could have surfaced as an automatically generated alert, and that the accident could have been prevented. (The technical investigations performed on the wreck of the helicopter also revealed that an O-ring between the gear shaft and the engine shaft was not in place. It is unclear what exactly the function of the ring is. In this account we attribute little significance to the absence of this ring. The accident investigation committee concluded in its report that the absence of the ring probably did not cause the mechanical failure of the splined sleeve, but that its absence could have increased the speed of crack development.)

INTRODUCTION OF HUMS INTO NORTH SEA OFFSHORE HELICOPTER TRANSPORT

In the following sections we will focus on the question of how and why a high-tech condition monitoring system that was designed and introduced with the specific aim to increase safety, why this system failed in its early warning function and why it failed to prevent the accident. To do this we must backtrack beyond the unserviceable sensor, and also beyond any human error or mistake or non-decision that could be attributed to individual mechanics in the HS hangar in Brønnøysund. Like random technical failures, human errors as causes are themselves results of more profound mechanisms and processes. This avenue of investigation takes us back to the middle of the 1980s.

Interactive fields with self-organising characteristics

The introduction of HUMS into the industry can best be understood in terms of an 'interactive field with self-organising characteristics'. This field comprises a set of actors interacting with each other through changing patterns of competition and collaboration. These patterns change and evolve over time and give rise to an emergent, global pattern of technological and organisational development that is underdetermined by rational or strategic intentions, decisions or policies of the actors involved. The plane of the field is horizontal. The image is not that of hierarchically organised levels with the state and regulatory bodies on top and oil companies and helicopter operating companies on the bottom. Regulatory bodies are actors on the same level of the field. In this case, the interactive field comprises actors that are in the business of regulating, providing services, producing and organising a system of interdependent flows (of oil, gas, equipment, spare parts, embodied competence, investment money and return revenues) requiring a high degree of regularity. *Regularity* refers to a systems capability to meet demands for delivery or performance.

Condition monitoring

During the 1970s and 1980s helicopters servicing the offshore industry in the North Sea were equipped with a cockpit voice recorder (CVR) only. Contrary to fixed wing airplanes they had no Flight Data Recorders (FDR). Neither were they equipped with vibration-based condition monitor systems.

The idea of real-time or 'in vivo' condition monitoring was not new; condition monitoring of machines had been developed for several decades. The size of measuring instruments and the size of mainframe computers necessary to handle large amounts of data gathered more or less continuously in real-time limited the applicability of these technologies. An increase in computational capacity that followed with the miniaturisation of microprocessors in the 1970s and early 1980s allowed for a reduction of the weight and dimensions of instruments for high speed data acquisition, processing, analysis and display. The development of software suites allowed the whole process of condition monitoring to be carried out automatically, giving a complete service for measurement, analysis and problem diagnosis followed by a maintenance strategy [6].

For aircraft, the confidence in continued airworthiness had long been based on the traditional method of maintaining safety margins by the prescription of fixed component lives and by aircraft 'strip-down' policies. Progress in engineering technology, however, allowed for replacement of some traditional failure preventative maintenance techniques by non-preventative techniques. It would also allow for a reduction of maintenance related costs. As the British Civil Aviation Authority (CAA) pointed out in 1990 [7]:

> Condition monitoring is not a relaxation of maintenance standards or of airworthiness control, it is, in fact, more demanding of both management and engineering capabilities than the traditional preventative maintenance approaches.

In 1984 the Helicopter Airworthiness Requirements Panel (HARP), appointed by the Airworthiness Requirements Board (ARB) of the British CAA, published its report on helicopter safety [8]. This report identified condition monitoring of critical transmission system components as having the potential to effect a significant improvement in airworthiness. The HARP-report was followed up with a 3-year research program starting in 1986 comprising two operational trials of health monitoring equipment on BHL (Bristow Helicopters)

Super Puma and BIHL (British International Helicopters) S61N aircraft undertaking normal North Sea support operations. These trials were completed in 1991 and are reported in [9].

Piggy-backing on FDR

Two conglomerates of companies (headed by Stewart Hughes and Bristow Helicopters respectively) asserted their mastery of the technology and were contracted to build prototypes, to install them on helicopters and run the trials.

In 1990, aiming to improve *post-hoc* accident investigation possibilities, the British Civil Aviation Authority issued new regulations that would make *flight data recording* (FDR) mandatory for all UK registered helicopters that would operate in hostile environments. Issued before the completion of the HUMS-trials in 1991, for supporters of condition monitoring in helicopters the FDR-directive provided an opportunity to move the HUMS-project forward and into the market. However, at that time practical experience with the prototypical HUMS-systems was rather limited. In the trials emphasis had been on the demonstration of technical feasibility of in-flight data acquisition for a variety of techniques. The system's capability and effectiveness in analysing these data to highlight abnormality, that is, its diagnostic and early warning capability, was not covered in the trial. The review of the trials published by the CAA concluded that [10]:

> . . . validating the effectiveness of the algorithm in detecting failure propagation was beyond the scope of the trial. With the limited flight time exposures it was not anticipated that significant failures would occur—nor did they. For reasons of resourcing and time scales the full suite of diagnostic algorithms planned for embodiment in one of the trial systems was not implemented . . .

Yet, companies involved in the development of HUMS, as well as the oil companies, themselves driving forces behind and sponsors of the HUMS trials—and co-operating in the UK Offshore Operators Association (UKOOA)—pushed for an integrated FDR/CVR/HUMS solution. The mandatory nature of the CAA's policy created an assured market for the manufacturers of the systems and quick returns on capital expenditures associated with production facilities.

In its product information Bristow Helicopters represented their system as a *ready-made* system that would generate large benefits for the helicopter operating company. It is worth quoting because it conveys the optimism and the high hopes that resulted from the *resonance* of a strong desire to improve safety, engineering judgement saying that it can be done and the prospect of economic profitability.

In a glossy product information brochure Bristow presented its system as 'THE ONLY INTEGRATED SYSTEM MONITORING FLIGHT SAFETY':

> Flight Data Recorders (FDR) will be a mandatory requirement from 1991 for all UK and USA registered Public Transport Helicopters (UK, all helicopters with an NTOW > 2730 kgs). Bristow Helicopters, one of the world's largest civil helicopter operators, have taken this opportunity to develop a COMBINED Flight Data Recorder, Cockpit Voice Recorder AND Health and Usage Monitoring System (HUMS) for installation in its twin engined helicopter fleet. The system has been developed by Bristow Helicopters and Plessey Avionics with Westland Helicopters supplying the gearbox vibration analysis techniques and MJA Dynamics providing the Rotor Track and Balance diagnostics. This combination of major helicopter operator with an avionics manufacturer, an airframe manufacturer and a leading engineering diagnostic systems specialist has lead to the development of a single integrated system which COMBINES Flight Data Recording, Cockpit Voice Recording AND Health and Usage Monitoring. This system will be for sale and available for installation to meet the 1991 FDR requirement both in the UK and in the USA. A recently completed computer study of helicopter accidents and serious incidents has indicated that the cause of 72% of the serious incidents and 55% of accidents in the study were likely to have been detected by the Bristow Health Monitoring System. The mandatory FDR installation will be a costly exercise. Maximise on the aircraft 'off-line' time by installing the combined FDR, CVR and HUMS on offer from Bristow Helicopters. As well as dramatically improving airworthiness of the helicopter the enhanced diagnostics offer considerable reduction in dedicated test flying. Bristow Helicopters are forecasting a reduction in vibration-related test flying on their Super Puma fleet by some 78%. Increased TBO and 'on condition' maintenance of major components can now become a reality.

To be fair, in the information packages presented to its customers, Bristow admitted that the system still had to mature. Therefore the system would be introduced in three phases [11]:

> During Phase I, the diagnostics associated with the advanced transmission vibration analysis . . . will be considerably extended and varied . . . 6 months of evolution in the diagnostic techniques are envisaged . . . the diagnostic suite will mature over a 6-month period from its Phase I standard introduced in February 1991. The basis for the MJ Dynamics diagnostics system is intelligent and will trend data self-amend as experience is gained. Phase 2 of the programme in addition to maturing the diagnostic suite and adjusting thresholds will be extending the diagnostic capability in the groundstation as new techniques which are already envisaged are applied to the groundstation for evaluation . . . During the later part of Phase 2 a programme will be commenced to look at the capability of on-board processing to give on-board display of parameters in areas where a possibility of propagation rates from detection to failure could be in the order of 5 or less flying hours. Phase 3, the airborne processing, will then be based on the known probability rates of false alerts and would include an expanded correlation of analysis . . . to further reduce false alarm rates . . . The display of values with the alerting of failures to the pilot will be on the basis of

> valid and extensive ground-based analysis . . . In Phase 3 it may also be possible to incorporate an entirely new system of signature diagnosis such as neural networks.

The time span envisaged for this maturation of the system was 3–4 years.

The Norwegian Helicopter Safety Study

On the other side of the North Sea helicopter-operating companies were 'observing' the developments in Great Britain. Two oil companies, *A/S Norske Shell* and Statoil, sponsored an extensive helicopter safety study carried out by SINTEF and published in 1990. The report concluded that a reduction in fatalities of approximately 40% might be achieved over the next 10–15 years, through extensive efforts in research and development. In this effort a focus on 'technical reliability' would yield the best results [12].

In its proposals for further *research and development* the Norwegian Helicopter Safety Study identified the 'effective use of operational experience for helicopters' as an area of research with high priority. The main objective for further *research and development* in this area should be: to develop a decision tool for maintenance based on safety ranking and operating data, in order to predict safe and economic lifetimes, and trace any reliability patterns [13].

Such a decision tool, it was argued, would contribute to optimal safety, regularity and maintenance cost. The proposed R&D-work should specifically focus on two aspects [13]:

- A method for criticality ranking of failure modes and failure symptoms.
- A method for data recording, analysis and presentation to identify trends and failure patterns, as a basis for maintenance decisions and eventually improved design requirements.

In its general conclusions the Helicopter Safety Study published in 1990 was in line with the British 1984 HARP-report. However, it advocated as topics for further R&D technical solutions that were already offered for sale as a ready made or off-the-shelf technology from Bristow/Plessey or Stewart Hughes. Hence, developments in Great Britain pre-empted the R&D-effort proposed in the Norwegian Helicopter Safety Study. The mandatory nature of the CAA directive precipitated the introduction of HUMS on British helicopters as retrofitted modifications of the extant helicopter fleet. Industry wide, oil companies licensed in the UK to explore and produce oil and gas implemented the CAA directive concerning FDR/HUMS in their contracts with British helicopter operators.

Norwegian civil aviation authorities (*Luftfartsverket*) did not follow the example of their British counterpart. In Norway there was no mandatory regulation requiring helicopter operators to equip their helicopters with CVR/FDR or HUMS systems. In Norway there was no counterpart to the UKOOA. In a less concerted manner, however, oil companies, who were clients on both the British and Norwegian continental shelf, started to introduce HUMS requirements in contract negotiations with Norwegian helicopter operators, thus introducing HUMS as a competitive factor in offshore helicopter transport in the Norwegian sector. In Norway, *Braathens Helikopter* was the first helicopter operator to issue a press release announcing that it would install HUMS on its whole fleet.

Helikopter Service A.S. was confronted with such HUMS requirements from customers but had at this point in time no clear strategy for the implementation of HUMS. The operations logistics of the company required flexibility in the deployment of its fleet of helicopters to meet the transport requirements of a variety of clients under different contracts. HS would not be able to guarantee one customer one helicopter equipped with HUMS, unless all helicopters were equipped with HUMS. HS had no choice. If the company wanted to (continue to) do business it would have to install HUMS on its whole fleet. 'If you don't have it, you don't play'. The decision to that effect was taken in the summer of 1991.

It is not unfair to say that decisions to introduce HUMS condition monitoring system in offshore helicopter transport in the North Sea were not based on the 'proven' merits of the technology (the next section will explore this issue further). In the interactive field of the North Sea petroleum industry, a desire to improve safety through regulations on the part of the British CAA (the CAA's Safety Regulation Group's motto, inscribed in stone at the entrance of its office building near Gatwick Airport, reads: *Safety is not an accident*) produced a mandatory directive on FDR. Due to the 'integration' of HUMS with CVR/FDR this decision propelled an 'immature' technological solution that had been pursued from a strictly engineering perspective, into a competitive market where major clients negotiated large contracts with a small number of providers of helicopter services. It gave those among the Norwegian helicopter operators that were willing to follow suit a competitive advantage in winning new contracts, forcing the others also to jump on the bandwagon.

Little attention was devoted to thinking about what the introduction of HUMS would imply for the maintenance organisation of a helicopter-operating company as a whole. The 'ready made' representation of the technology and of what it could do for safety and for costs corresponded well with the notion of helicopter operating companies as *users* of technology. This *representation of the technology* seemed to fit well with the standing operating procedures of the organisation. Once in place, the HUMS system would generate automatic alerts that would guide and focus 'downstream' maintenance and engineering attention to the correction of gradually developing degradation failures in safety-critical components and thus help to detect and prevent imminent accidents. In practice it did not work out that way.

THE INTRODUCTION OF HUMS IN HELIKOPTER SERVICE A.S.

The HS Engineering Department

Being rather successful in its field HS had, in the late 1980s and early years of the 1990s, a relatively large engineering and design department, employing approximately 25 engineers. On one hand this department was responsible for the articulation and updating of maintenance and other technical procedures in accordance with regulations issued by Norwegian civil aviation authorities. The department also worked on the development and implementation of a system for reliability monitoring and reliability management: definition and measurement of reliability parameters, extraction of failure data from aircraft logs and maintenance work cards, analysis techniques and establishment of a platform within the technical and maintenance organisation where results were evaluated and where decisions were taken to change and optimise the quality of performance of the maintenance organisation as a whole. The department also worked on the design and installation of not safety critical equipment, ranging from interior design modification (improving comfort) to the installation of searchlights. At all times at least four engineers were dedicated to work on condition monitoring and reliability issues.

Two engineers employed in the engineering department worked on experimental vibration-based condition monitoring of helicopters. Using equipment that was available at the time, and that was used in for example fixed wing airplays, they tried to find an arrangement (distribution and type of sensors, registration format) that could provide valuable information about the condition of safety-critical components. Of course, part of this work involved finding ways to process and interpret the data collected in this way. Registrations were typically conducted with large time intervals, perhaps 50 or 100 operational hours for a specific helicopter. The data were then analysed off-line, but at this stage there was no direct or regular feedback of this information into the maintenance organisation.

The techniques and skills developed in the engineering department were used in complicated trouble shooting activities. When normal maintenance and trouble shooting procedures failed to detect the cause of and eliminate a problem with a helicopter experienced by a pilot, the helicopter could be temporary equipped with the (experimental) vibration monitoring equipment, either during test flights or during continued service with intensified monitoring.

This engineering department was not involved in day-to-day helicopter operations. Within the company these engineers worked in a largely unregulated space in an organisation that was otherwise geared towards the regular provision of helicopter transport services to major clients in the offshore industry. Not being subjected to the regularity press of daily operations the engineers had time and space for trial and error, for hands-on work on helicopters, monitoring equipment and the registrations these produced. Through the practical experience gained in this work, within the company these engineers developed the most sophisticated intuitive understanding of the dynamic characteristics of a helicopter and its vibration patterns. They were also fascinated by the new condition monitoring technologies that were finding their way into the helicopter industry.

The HS HUMS procurement policy

When in the summer of 1991 upper level HS management decided to install HUMS on its helicopter fleet, this resonated well with the engineering department's fascination for the new technology. They would be involved in the evaluation of available systems, in the choice of manufacturer and system and, not least, in the installation of HUMS on the helicopters. Functionality, technology and philosophy of the two available systems, Bristow/Plessey and Stewart Hughes, were compared and evaluated. Whereas Braathens Helikopter and another Norwegian helicopter operator, *Mørefly*, chose Bristow/Plessey systems, HS negotiated a contract with Stewart Hughes for combined FDR/HUMS-systems for 13 of its helicopters, eleven S61N and two Boeing 234. In developing and negotiating the technical and functional specifications of the system Helikopter Service engineers aimed for sophistication. As many sophisticated and automated features as possible should be included in the 'box', that was envisioned to be able to perform a total and integrated diagnostic of the helicopter's condition, either for the purpose of off-line and out-of-service testing, or for the purpose of operational, in-service condition monitoring. The specifications of the contract did not include the installation itself. Helikopter Service chose to do the installation work in house [14].

Soon after the conclusion of the contract with Stewart Hughes in the summer of 1991 intensive construction work on the first helicopter, a Sikorsky, began in September 1991 and was completed in November of that year. Installation work on the other Boeing and Sikorsky helicopters continued during the next year 1992. These HUMS systems, as they were delivered for retrofit installation on helicopters already in service, were no 'plug-and-play' solutions. Although supported by installation instructions, installation of the system required a lot of testing to determine the optimal locations for the placement of the various vibration sensors. The installation of HUMS systems constituted an engineering challenge in itself that consumed much of the engineering department's time and resources.

While concluding the contract with Stewart

Hughes for the delivery of HUMS systems for the company's Sikorsky and Boeing helicopters, HS postponed the decision to install HUMS on its Super Puma helicopters because the company intended to buy new Super Puma Mark II helicopters from the French helicopter manufacturer *Eurocopter*. HS wanted to use its buyer position to obtain a HUMS system that was integrated into the helicopter—instead of retrofitted—and thus supported by the helicopter manufacturer. Furthermore HS wanted this system to be logistically compatible with the HUMS systems installed on its Sikorsky and Boeing helicopters. Eurocopter negotiated a contract with Stewart Hughes/ Teledyne but was not able to develop and install the new HUMS system on the first new Super Puma helicopter delivered to HS, neither on the second.

In 1993 HS negotiated a contract with Eurocopter pertaining to retrofitting the company's Super Puma helicopters with EuroHUMS systems. By then however, the central Data Acquisition and Processing Unit of the Stewart Hughes systems had been replaced and upgraded as a result of which the operational compatibility with the HUMS systems on the Boeing and Sikorsky helicopters was lost [14, pp. 8, 9]. In subsequent years, HS acquired several of its helicopter operating competitors in the Norwegian marked, Braathens Helikopter and Mørefly. In the early 1990s these companies had opted for the HUMS-system offered by Bristow. As a result, in 1997 HS operated three different versions of HUMS. LN-OPG, the helicopter involved in the 1997 accident originally belonged to Mørefly. Hence it was equipped with a Bristow/Plessey HUMS system.

The HS investment plan that had been prepared to manage the introduction of HUMS allocated money to the technical installation of the systems but did not recognise the necessity to invest time and energy in a systematic consideration of the consequences of HUMS for the company's maintenance organisation. The consequences were considerable and can be distinguished as pertaining to:

1. the maintenance of the HUMS system itself, and
2. the interpretation of the data patterns generated by the HUMS system.

The former has to do with the necessity to work the HUMS systems not only into the hardware of the helicopter but also to retrofit the system as an add-on to an existing maintenance organisation, maintenance procedures and manuals and maintenance routines. HS bears the characteristics of bureaucratic work organisations that pervade the entire field of civil aviation [15]. Detailed maintenance manuals, made up of a great number of work cards, describe very specifically the investigative procedures and corrective actions to be carried out within a specified timeframe by the line mechanic in specific situations of component failures. These manuals, which are worked out by the engineering department and the helicopter type engineers, constitute the primary frame of reference for the line mechanic. These manuals serve to reduce the level of uncertainty for the mechanics involved in day-to-day (first line) maintenance work of helicopters. They specify which situations can be handled by the line mechanic and how. The manuals also distribute responsibility in a specific way. The engineering department and helicopter type engineers are responsible for the content of the manuals, whereas compliance with these manuals defines whether the line mechanic has done a good job. Hence, the maintenance work on helicopters is highly regulated.

Within this highly regulated work organisation the introduction of HUMS created an *unregulated space*. The latter consequence, having to do with the interpretation of the data patterns generated by the HUMS system, was in a sense more profound because it affected the level and distribution of *cognitive uncertainty* in the maintenance organisation. In practice, interpretation and maintenance problems compounded each other in confusing ways.

Uncertainty

Taking the automatically generated HUMS alert as a reference point the problems confronting maintenance personnel can be distinguished in upstream and downstream problems. Downstream problems had to do with inconsistencies in automatically generated associations between specific alerts (and types of trends in parameters) and the references to work cards (in the helicopter maintenance manuals) that would describe the corrective action to be taken. There was also an insufficient fit between the references to work cards generated by the HUMS system and the actual helicopter manuals in use at HS. If often happened that the systems referred to work cards that had nothing to do with the component that was indicated as having a problem by the alert. These problems were irritating and time consuming. They hampered the smooth integration of HUMS in the highly regulated work organisation of the HS maintenance organisation. However, they did not exhibit the cognitive uncertainty encountered in upstream problems.

Upstream problems have to do with the generation of the signal and the generation of the alert, that is, with false positive and false negative alerts. False positive alerts prove wrong the assumption underlying the idea of failures producing unique signatures; that only the degradation in the monitored system generates an alert, or that the software would be able to distinguish the 'signal' from the noise; that the set of threshold values would act as an effective filter. These problems are well known from other indirect technical measurement, observation or monitoring arrangements where they are framed in terms of *specificity* and *sensitivity*:

- Does the arrangement measure what it is supposed to measure?
- Is it *specific* enough: does it *only* measure what it is supposed to measure, or are there other processes that can mimic the phenomenon that the arrangement is supposed to measure?
- Is the arrangement *sensitive* enough: if there is a deviation from normal, does it turn up as a positive result?
- Does the absence of a deviation always yield a negative result?

In theory the ideal measurement arrangement would be simultaneously very specific and very sensitive (and easy, quick and cheap to perform). It is this ideal that we find in Bristow's 'ready made' representation of HUMS' capabilities and in the Barron's formulation of what an ideal condition monitoring system could be. In practice the two do not go very well together.

The experiences of HS with HUMS suggest that the system is not very specific and is ambiguous in its sensitivity, resulting in a low 'alert reliability'.

The experience rate of the helicopter being in a critical failure state, given a random alert is typically 1 in 200 alerts, or 0.005. This figure can be interpreted as a measure of alert reliability [16]. CAA Paper 93002, authored by Bristow Helicopters Ltd. [9], recognises this problem of frequent false positive alerts, suggesting that Bristow's practical (trial) experience with HUMS was no different from Helikopter Service's.

Failure modes

In the engineering literature on condition monitoring engineers are occupied with the problem of how to model known failure modes in algorithms and data processing software. A failure mode is defined as the manifestation of a failure as it can be observed on the item. This presupposes the presence of human senses (aided or unaided by technical means). It is also very analytic, in the sense that it considers discrete items with clearly defined boundaries. The notion of a failure mode is part of a vocabulary developed in the context of quantitative failure, risk or reliability analysis. These are desktop exercises—tools that can help to make choices in the design of new technical systems or to evaluate changes in existing ones. They describe the discrete components, down to the level of the smallest maintainable item, and how these are hierarchically assembled in subsystems and systems. For each item the required functions are described as well as the ways in which they can fail. Estimated or 'experienced' values for failure rates are used to calculate probabilities.

Hence, failure modes are part of an activity were you think through the technical system and try to imagine all the ways in which it can fail. It is the mind's eye that is doing the observing. Especially in reliability-centred approaches, employing field performance information, the content of the failure mode descriptions *derives* from maintenance work, mostly 'off-line'. They are descriptions as they appear in maintenance logs. But maintenance engineers produce discreteness of the items through their interventions. They take the technical systems apart, hold them in their hands, describe what they see with their unaided eyes or though the application of special techniques that help to visualise what they cannot see with their unaided senses.

Hence, it is difficult to relate the notion of failure modes to the fully integrated and operational technical system of a helicopter in flight. In this on-line operational mode of the system there are no human senses present to observe failure modes. Perhaps that is not correct. The helicopter pilots are there and they have senses. The proprioceptic sense organs that are distributed in their bodies and that connect to nerve endings register the vibrations in the helicopter and might detect aberrant vibration patterns, like a car driver might detect abnormal vibration patterns in the steering column or the body of the car. However, most of the time the pilots' senses are occupied with flying and navigating the helicopter, and they should be. Only in a very limited extent are failure modes, indirectly and mediated through technical monitoring systems, presented to the helicopter pilots in their cockpit. For example, when an engine runs into overspeed a light comes on in the cockpit. The overspeed protection system will automatically shut the engine down. (The standard operating procedures to which the pilot is subject require him not to restart the engine. In the 1997 helicopter accident, recovered cockpit voice recordings indicated that the overspeed indicator came on briefly, suggesting that the overspeed protection system was activated, as a result of the failure of the engine's driving shaft, before it was destroyed.)

HUMS constitutes an attempt to have the maintenance engineer's senses present in the operational, flying helicopter, although in an externalised or delegated sense. But the discreteness of items or components that the notion of a failure mode presupposes is not present in the flying helicopter. The engine and gearbox housings are bolted together forming a physical unity vibrating as one with the helicopter as a whole. The high speed engine shaft is physically engaged with the gearbox shaft that is transferring the power of the engines to the rotor system, forming a single dynamic power train that, through the rotor's interaction with air and wind, provides the helicopter with lift and forward thrust.

The HUMS sensors are strategically placed, not on discrete components, but on the surfaces of a physically integrated, air-beating and vibrating whole. Vibrations do not respect component boundaries. They may be amplified or dampened, depending on the characteristics of the material through which they travel. The vibration sensors contain a small seismic mass that is surrounded by, or perhaps better, suspended in a piezo-electric substance. Movements of the seismic mass produce small changes in the electrical field generated by the piezo-electrical substance. Hence, the sensors provide electrical signals that are acquired by the DAPU. Because this data collection is not continuous but cyclic, the acquired signals provide discrete batches or strings of data that serve as input for the software performing the analysis, calculating parameters and comparing them with pre-set threshold values.

The basic problem is to figure out how degradation failures in for example engine or gearbox shafts express themselves in the vibration patterns generated by the HUMS systems and software. To some extent engineers have succeeded in doing this by assuming that the deviant vibration pattern produced by an engine shaft rotating at a certain speed will be cyclic, that is, it will repeat itself with the frequency of the rotating shaft. This forms the basis for the extraction of this pattern from the background noise of vibrations generated with other frequencies.

So-called 'seeded fault tests' have been very helpful in this process. Under controlled laboratory conditions engineers 'inflicted' failures and damages on components, reinserted them in the technical (sub)system, ran it and monitored the resulting changes in vibration patterns. These procedures helped to improve the systems *sensitivity*, but did little to improve its specificity under circumstances of in-flight (in vivo) condition monitoring. Due to the system's sensitivity some imminent failures were discovered and accidents prevented. Helicopter operating companies can point to these experiences and admit that, yes, in some cases the system worked. The system's poor specificity, however, is responsible for the large amount of false positive alerts.

SELF-ORGANISATION OF ROUTINES THROUGH FALL-BACK ON ESTABLISHED PRACTICES

The space that the introduction of HUMS in HS created was not only unregulated, it was also full of uncertainty. In the absence of a procedural frame of reference, or some other kind of external source of order, this unregulated and uncertain space allowed for the establishment of action patterns in handling HUMS component failures that came about through processes of self-organisation.

Soon after the first HUMS systems came into operation HS line mechanics and HUMS-engineers in the company's engineering department encountered the first automatically generated alerts. Troubleshooting searches involving the HUMS system itself as well as the helicopter often remained fruitless. HUMS itself became a source of impediment for the helicopter's uptime. The long searches generated maintenance costs rather than reducing them. As all components do, HUMS components also began to fail. It turned out that sensor-related failures often pertained to the junction between the sensor housing and the electric cable that was attached to it. There were no maintenance manuals to which line mechanics could refer and obtain guidelines for the appropriate courses of corrective action. The system over which HS engineers assumed to have gained control through the in-house installation, now turned out to generate frequent and new problems on its own. Through daily interactions with the technology, with automatically generated alerts, extensive trouble-shooting searches and failing components, line mechanics and HUMS engineers struggled to make the system work and to regain control over the technology. That is, to develop locally reasonable effective working solutions and routines that would: minimise the uptime impediment *due to* HUMS warnings (false) or defective HUMS system components, minimise the maintenance cost *imposed by* HUMS, while allowing them to read vulnerable situations as best as possible and give senior management and customers the impression that they were dealing with the system and that *they were in control*.

Increasingly the Engineering Department that had been relatively secluded from the regularity press of daily helicopter operations became more and more involved in these daily operations.

Considering that a) HUMS was not mandatory in Norway, b) its automatically generated output was unreliable in the sense that only 1 in about 200 alerts could be substantiated, and c) faulty sensors or other HUMS components were not considered to influence the helicopter's safety and airworthiness (that was determined by the technical integrity of the helicopter's power train), in their handling of component failure technicians and engineers fell back on already established routines with regard to non-safety-critical component failures in helicopters. Psychological human factor research looking into the behaviour of people in crisis situations has identified a mechanism called *regression to first learned responses*. See [17]. (In crisis situations communication breaks down, causing confusion and uncertainty. In stead of 'choosing' the 'appropriate' response from the recently learned and accessible responsive repertoire, the subject under stress regresses to older, first learned but in this crisis situation usually inappropriate responses, thus causing fatal accidents. The word 'regression' carries negative connotations. However, the mechanism might be similar: a fall-back to established and proven practices.)

Minimal equipment lists (MEL) define the components and technical subsystems that must be fully operational to allow a helicopter to be authorised for service. Conversely, the MEL also defines which components may be defect and for how long without precluding the release of the helicopter for service. When corrective action cannot be taken immediately or is not deemed necessary before the next scheduled maintenance session comes up, these defect items may be entered on a 'deferred defect list' that is kept for each helicopter. Although there was no MEL for the HUMS systems, the MEL practice that is accepted and approved throughout the civil aviation industry, served as a template for the formation of new working procedures with regard to HUMS systems. Subsequently these reasonably workable procedures and ways of doing and handling things became subject to what Starbuck calls 'programming', they become part of the organisation's informal routines [18].

When a defect HUMS sensor was discovered on LN-OPG in 1997, an attempt was made to repair it, but this attempt failed. In concurrence with a by now established practice—that had 'self-organised' itself through the troublesome interaction of maintenance personnel with frequent component failures and false positive alerts against a background of an already established routine formalised in MELs and deferred defect lists—the repair of the sensor was deferred to the next upcoming opportunity. In the absence of a HUMS specific MEL specifying a timeframe for the repair, in this case no specific time for the repair was set. The sensor was still 'unserviceable' when the accident occurred.

VULNERABILITY AND DRIFT ALONG A REGULARITY GRADIENT

The defect sensor cannot be said to have caused the helicopter accident. The same holds for the decision to defer the repair of the sensor, if at all, it is sensible to speak of a 'decision' when referring to action patterns that have become part of an organisations informal routines. In a helicopter-operating company that must be in a 'routine mode' instead of a 'problem-solving mode' in order to meet the regularity requirements of the offshore petroleum industry, programming—either formalised or spontaneous and unreflected—helps to achieve the organisation's goals by filtering information and focusing attention on the company's resources.

HUMS was introduced prematurely, in the industry and in Helikopter Service A.S., as a result of the resonance of a desire to make helicopter transport safer, with an engineering fascination of new sophisticated technology, and the anticipation of economic profitability with the necessity to remain competitive. This induced in the heterogeneous system of the helicopter and its maintenance organisation a *drift* towards a more *vulnerable* state that included the explicit acceptance of sub-optimal states in the helicopter's technical systems. (For notions of drift in a variety of disciplines see [19]. For notions of vulnerability see [20].) This in turn diminished the systems capacity to anticipate, cope with, resist, and recover from the impact of a critical degradation failure. As a result, an imminent failure was not discovered that could have been detected had the HUMS system been fully operational.

The basic image is one of a heterogeneous, open and adaptive system tracing a path through a space of possible states. Towards the periphery of this space there are vulnerable regions that are characterised by the occurrence of multiple sub-optimalities. At the centre we can imagine an area that reflects an ideal condition in which technical systems are fully operational. Work performance by machinery and by operational and maintenance personnel is optimal and in compliance with technical and job performance specifications and safety regulations. Goals and means match. Furthermore, there is a high or absolute degree of compatibility and coherence between goals that have to do with production, economy, safety and environment. This is where reliability coincides with safety and availability to guarantee regular and cost-effective overall system performance. However, this is an ideal representation of a technological and organisational space as it may be found in blueprints or the design imagination of engineers. We will call this ideal representation 'protocol'.

In practice however, the system will never remain long in that ideal condition. The system will always be subject to drift, fuelled by situated processes and mechanisms that result from local interactions between human workers and between humans and the technologies they work with. Hence, there will always be a gap, a delta, between protocol and practice. This protocol-practice gap is not static and fixed, but fluid and changing.

We may postulate the existence of a 'regularity gradient' influencing the formation, extent and direction of the protocol-practice gap. This regularity gradient eventually ties our industrialised society's dependency on fossil fuel energy, and our economy's craving for quick revenues from invested capital, to the formation of working routines in local workplaces in helicopter base hangars. Society's dependence on fossil fuel energy induced Statoil to contractually bind itself to the delivery of oil and oil products from the Norne field long before the field was developed. The unavailability of the Norne ship after the scheduled start of production on October 1, 1997, would cost the company a lot of money. Statoil's efforts to meet this deadline translated to Helicopter Service A.S., the helicopter operator that, with an average of 1800–2000 flight hours per helicopter per year, was already utilising the capacity of its fleet and pilots to the fullest. It is under these conditions that the regularity gradient causes production (the provision of helicopter transport for clients) and safety goals to diverge.

As far as HUMS is concerned the system was never at the ideal centre location that we called protocol and that was articulated by Bristow and Plessey in their product information materials and by Barrom in the engineering literature on condition monitoring. The HS maintenance organisation could never live up to the high expectations held by the company's senior management and by oil company clients. In hindsight we can see that there were no realistic ways in which to balance the diverging goals of availability for production, economy and safety.

Not contradicting upper management's customer's assumption that the HUMS systems were always fully operational and that an unserviceability of the system would ground the helicopter, the base maintenance organisation realised how ridiculously contradictory such a requirement would have been with the overall goals of the operation (up-time, cost, etc.). Hence, there was not only a gap between protocol and practice, between an idealised state and actual working conditions. There were also inconsistencies, a dislocation, between actual practice in the base maintenance organisation and senior management and client-held assumptions about system conditions. Although the establishment of these ad-hoc routines and dislocations contributed to the system's vulnerability, for several years the system's overall performance in term of production and provision of service was acceptable.

Before the accident on September 8, 1997, there was no Minimum Equipment List (MEL) for HUMS. Following the accident and the discovery that the sensor in question had been unserviceable, there was an outrage by customers, senior management, aircraft accident investigation board and public in general that such an unserviceability could have happened. All the other helicopter operators rushed in to state or hint that such a situation could not have happened in their operation. (Obviously, these were first responses that had to be modified later. According to Bristows Helicopter's Ian Dobson, IHUMS Type Engineer, in response to the accident at the Norne field, Bristow too had to review all its procedures and routines concerning HUMS, suggesting that the way of dealing with HUMS at HS was not confined to Helikopter Service A.S.) When the smoke had settled, it turned out that none of the operators did have any procedures in place, not to speak of a MEL. The MEL for HUMS evolved as a mutual helicopter operator effort early 1998. The Norwegian oil operators and helicopter operators established a common forum to develop a Norwegian standard which is now part of standard contract requirements. The British CAA has since made such HUMS MELs mandatory.

It is important not to confuse the idealised representation that we called 'protocol' with formal regulations and procedures approved by regulatory bodies. The MEL for HUMS itself is a *pragmatic adaptation* to the regularity requirements of the industry, a consolidation of a compromise between ideal targets and what are perceived as realistic limitations. Approved, certified and legitimised by civil aviation authorities the MEL for HUMS reflects the degree to which the actors in the field accept the existence and persistence of sub-optimal, that is, vulnerable states and conditions. Given the current reliability of HUMS outputs and components, the allowance of this deviation from an optimal, fully operational state is necessary 'to keep the rotors turning'. And because the deviation is formalised and legitimised the system's vulnerability will be perceived as an unavoidable, static and structural overall characteristic of the system.

CONCLUDING REMARKS: WHERE TO GO FROM HERE?

Our emphasis in this paper has been on the development of an understanding of what happened; on making sense, rather than on providing solutions or management tools. On the basis of our analysis we can make two tentative suggestions, though.

First, concerning the development of HUMS it seems to be obvious that a considerable effort should be made to improve the system's diagnostic specificity, that is, to reduce the number and frequency of false positive alarms. First of all this requires a recognition and acceptance of the fact that HUMS-systems today are not a ready made technology. It is not a commodity to be bought off the shelf. Second, this requires the recognition of a dual role for helicopter operating companies. They are not only *users* of technology; with regard to HUMS they should also consider themselves, and by others they should be considered as *developers* of technology. There is a growing body of literature that emphasises the importance of networks (of companies, private and public research institutions) for the development and innovation of highly complex products and systems (CoPS) [21]. With regard to the development of HUMS helicopter-operating companies would be of central importance in such a network. A network of companies and institutions devoted to the development of HUMS would need to facilitate the flow of data and information between users and manufacturers. Such a network should create a place where data, information and experiences of users and manufacturers can be juxtaposed and compared. Civil aviation authorities should play an active role in facilitating and financing such a network. The formation of such a HUMS innovation network requires a fundamental rethinking and rearrangement of current economic and contractual relationships between manufacturers, users, clients and regulatory bodies. For over a decade now traditional contractual relationships between companies have impaired the development of HUMS. Even if Bristow's 3–4 year time span for the 'maturation' of HUMS was far too optimistic, more progress should have been made in the past decade. Due to high certification costs of subsequent changes, certification of HUMS at this point would severely impair or lame the development, resulting in a lock-in of the system in its current unreliable state.

The second suggestion we would like to make concerns the issue of (organisational) drift into more vulnerable states. It is fair to say that all organisations are subject to drift. Whereas reliability engineers have developed sophisticated tools to monitor drift in mechanical production systems, there are remarkably few 'tools' that aim to discover and monitor drift in design and engineering, operational and maintenance organisations. In the heterogeneous, open and adaptive systems that organisations are—including the technologies they operate—drift is the organisation directly influences and thus produces the reliability and vulnerability of the technical system.

It is important that organisations develop sensitivity for these messy, locally interactive and adaptive processes that lead to drift. This sensitivity should not only be developed by the human actors at the sharp end, but also among the leadership of organisations. Part of developing such a sensitivity lies in providing images, metaphors and concepts, words, that can be used to describe and express what often is already known intuitively. This implies that developing sensitivity for these processes does not necessarily require a sophisticated social science background. To a large extend it is a matter of activating and articulating experiences, perceptions and understandings that are already there.

It is important that companies create a more general 'function' within their organisation that scrutinises working practices, routines and procedures on a continuous basis to detect, evaluate, monitor and map organisational drift. The function must be protected from the regularity gradient that affects the operational and maintenance organisation and also can assist in the organisational redesign and fitting that should follow with the introduction of new technologies like HUMS. The function suggested here should be reflective, interrogative towards one's own organisation, and has nothing to do with verification of compliance with formal regulations and procedures. A focus on the messiness of drift and vulnerability is at variance with current quality assurance paradigms, as they appear in ISO 9000 codes and standards. These require a rigidity, stringency and consistency that do not conform to this fluid reality.

A focus on vulnerability is very different from an outcome and event-based safety management strategy. Although increased vulnerability may eventually express itself in an increase in accident or lost time statistics, these statistics will tend to lag behind an increase in vulnerability, because vulnerable conditions for a long time may be associated with acceptable outcomes. A focus on vulnerability would also do away with the distinction between objective risk (as expressed in outcome-based statistics) and subjective risk perception. A focus on vulnerability would appreciate subjective risk perceptions of sharp end workers as expressions of an understanding that relates to (changes in) a system's vulnerability.

These are profound implications with ramifications that extend the domain and reach of influence of leaders and managers in individual companies. However, we would be ill advised if we followed Reason's suggestion to judge 'models of accident causation' only to the extent to which their applications enhance system safety. Reason argues that [22]:

> . . . the economic and societal shortcomings . . . are beyond the reach of system managers. From their perspective such problems are given and immutable. But our main interest must be in the changeable and the controllable. For these reasons, and because the quantity and the reliability of the relevant information will deteriorate rapidly with increasing distance from the event itself, the accident causation model presented. . . must, of necessity, be confined largely to the manageable boundaries of the organisation concerned.

Our argument is that because organisations are open, adaptive systems, we must consider influences and processes that go beyond the boundaries of the company. Our notion of a regularity gradient is intended to span the distance from an industrialised society's global dependence on the continuous and regular provision of fossil energy sources to the local adaptations and struggles and frustrations to deal with uncertainties at a helicopter base in Brønnøysund. Influencing global regularity requirements for fossil fuels will be out of reach for most of us. This does not mean that there are no practical issues to engage in one's own working environment.

Acknowledgements—We would like to thank the Centre for Technology and Society at the Norwegian University for Science and Technology in Trondheim, Rogaland Research in Stavanger, and the Centre for Technology, Innovation and Culture at the University of Oslo for offering office space during a number of research visits to Norway, allowing us to do the empirical research and most of the writing of this paper.

REFERENCES

1. AAIB-N (Norwegian Aircraft Accident Investigation Board), Rapport om luftfartsulykke 8. September 1997 i Norskehavet ca. 100 nm vest-nordvest av *Brønnøysund med Eurocopter AS 332L1 Super Puma, LN-OPG, operert av Helikopter Service AS*, Norsk Aero AS, Oslo, Norway (2001).

2. W. E. Bijker, T. P. Hughes and T. Pinch (eds.), *The Social Construction of Technological Systems. New Directions in the History and Sociology of Technology*, MIT Press, Cambridge, MA, (1987).
3. Statoil, *Rapport fra konserngranskningen etter helikopterhavariet ved Nornefeltet 8. September 1997*, Statoil internal report, Stavanger, November 6, 1997.
4. Per Hokstad, Erik Jersin, Geir Klingenberg Hansen, Jon Sneltvedt and Terje Steen, *Helicopter Safety Study 2*, SINTEF, Trondheim (1999).
5. AAIB-N, op. cit., p. 162.
6. R. Barron (ed.), *Engineering Condition Monitoring. Practice, Methods and Applications*, Longman, Harlow (1996).
7. CAA, *Condition Monitored Maintenance*, CAP 562, Civil Aircraft Airworthiness, Information and Procedures, Part 1: Airworthiness Procedures, Leaflet 1–7, The Civil Aviation Authority, London (1990) p. 3.
8. CAA, *Review of Helicopter Airworthiness*, Report of the Helicopter Airworthiness Review Panel (HARP) of the Airworthiness Requirements Board, CAP 491, The Civil Aviation Authority, London (1984).
9. CAA Paper 93003, *Helicopter Health Monitoring, Bristow Helicopters Ltd—Operational Trial of Helicopter Health Monitoring Techniques*, Civil Aviation Authority, London, February 1993; and CAA Paper 93004, *Helicopter Health Monitoring, British International Helicopters Ltd—Operational Trial of Sikorsky S61N Health and Usage Monitoring System Demonstrator*, Civil Aviation Authority, London, February 1993; CAA Paper 93002, *Helicopter Health Monitoring, Operational Trials Review*, Civil Aviation Authority, London, February 1993.
10. CAA Paper 93002, op. cit., p. 18.
11. Bristow Helicopters Limited, *Integrated Health and Usage Monitoring System: An Introduction to the Bristow iHUMS system*, 25th January 1991, pp. 5–6.
12. O. Ingstad *et al.*, *Helicopter Safety Study. Main Report*, SINTEF, Trondheim (1990) p. 3.
13. Ingstad *et al.*, op. cit., p. 121.
14. J. Kørte *et al.*, *HUMS Evaluering*, internal report, Helikopter Service A.S., Stavanger (1998) p. 8.
15. P. Thompson and D. McHugh, *Work Organisations: A Critical Introduction*, MacMillan Press Ltd., London (1990) p. 158.
16. J. Kørte and T. Aven, Health monitoring or helicopters—a framework for decision making based on health information, in M. P. Cottam, D. W. Harvey, R. P. Pape, and J. Tait, (eds), *Foresight and Precaution*: *Proc. ESREL, SARS and SRA-Europe Annual Conference*, Edinburgh/Scotland/United Kingdom 15–17 May 2000, Volume 2; A. A. Balkema, Rotterdam/Brookfield (2000) pp. 933–940.
17. K. E. Weick, Vulnerable system: an analysis of the Tenerife air disaster, in P. J. Frost *et al.*, *Reframing Organisatonal Culture*, Sage Publications, London, (1991) pp. 117–130.
18. W. H. Starbuck, Organisations as action generators, *American Sociological Review*, **48** (1983) pp. 91–102.
19. S. A. Snook, *Friendly Fire: The Accidental Shootdown of U.S. Black Hawks over Northern Iraq*, Princeton University Press, Princeton, NJ (2000); C. U. Ciborra *et al.*, *From Control to Drift. The Dynamics of Corporate Information Infrastructures*, Oxford University Press, Oxford, (2000); E. E. Lewis, *Introduction to Reliability Engineering*, 2nd Edition, John Wiley & Sons, Inc., Chichester (1994) p. 90.
20. R. Rosness, Vulnerability in complex systems: Directions for research, (working paper), NTH, Trondheim, (1992); P. Blaikie *et al.*, *At Risk: Natural Hazards, People's Vulnerability and Disasters*, Routledge, Londen (1994) p. 9; NOU *Et sårbart samfunn. Utfordringer for sikkerhets- og beredskapsarbeidet i samfunnet*, Norges offentlige utredninger 2000:24, Statens forvaltningstjeneste Informajsonsforvaltning (2000) p. 21; S. Einarsson and M. Rausand, An approach to vulnerability analysis of complex industrial systems, *Risk Analysis* **18**(5), 1998 pp. 535–546, p. 535; S. Einarsson, *Vulnerability and Risk Analysis of Complex Industrial Systems: A New Approach and Discussion of Main Problem Areas*, Doctoral Thesis, The Norwegian University of Science and Technology, Department of Production and Quality Engineering, Trondheim, (1999); C. Perrow, *Normal Accidents. Living with High-Risk Technologies*, 1999 edition with an Afterword and Postscript on the Y2K problem, Basic Books, New York (1984/1999).
21. M. Hobday, Innovation in complex products and system, *Research Policy*, **29**(7,8), August 2000, pp. 793–804; D .E. Kash and R. W. Wycoft, Patterns of innovating complex technologies: a framework for adaptive network strategies, *Research Policy*, **29**(7,8), August 2000, pp. 819–831. Available through the Internet on: http://www.elsevier.nl/homepage/sae/econbase/respol/
22. J. Reason, *Managing the Risks of Organisational Accidents*, Ashgate, Aldershot, (1997) p. 16.

Ger Wackers, MD, 1986, Ph.D. in science and technology studies from the University of Maastricht, 1994. Assistant professor at the Department of Technology and Society Studies, Faculty of Arts and Culture, University of Maastricht. Currently working on a larger project on issues of reliability and vulnerability of complex technical systems in the North Sea offshore industry.

Jens Kørte, M.Sc., mechanical engineering from Norwegian University of Science and Technology, NTNU, 1982. Consulting and research work in mechanical engineering and reliability issues. From 1989: managerial positions with Helikopter Service, a major helicopter operator in offshore oil support. Since 1999: Ph.D. fellow at Stavanger University College working on organisational risk management and decision making.