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Resonating Cultures:

Engineering Optimization in the Design and (1991) Loss of the Sleipner A GBS

Ger Wackers

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

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Center of Technology, Innovation and Culture
University of Oslo
Gaustadalléen 21
P.O. Box 1108 Blindern
N-0317 Oslo
Norway

Senter for teknologi, innovasjon og kultur
Universitetet i Oslo
Gaustadalléen 21
0349 OSLO
http://www.tik.uio.no/
Telefon: 22 84 06 00
Telefaks: 22 84 06 01
E-post: info@tik.uio.no

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Contents

Preface

Complex technological systems that perform reliably most of the time, fail unexpectedly and dramatically sometimes. Examples abound: the accidents with the space shuttles Challenger and Columbia, Chernobyl, the ferries Herald of Free Enterprise and Estonia, several civilian airliners, the Piper Alpha disaster and its Norwegian counterpart in terms of human lives lost in the North Sea offshore industry: Alexander Kielland. In recent years Norway experienced several unexpected large scale accidents involving complex technological systems: the crash, in 1997,of a Super Puma helicopter (LN-OPG) en route to the floating oil production platform at the Norne field, the loss of MS Sleipner at Store Bloksen in 1999, the train collision near Åsta on the Røros line in 2000. Despite the major differences in types of technology involved, what all these examples have in common is that the organizations that operated the various complex technological systems were not able to maintain functional and technical integrity; they were not able to maintain *performative closure*.

Many of these accidents result in public inquiries; when there is environmental damage or when human lives are lost. These investigations generate information and materials about company internal mechanisms and processes that would otherwise not be available to ‘outsiders’. Hence, these large scale accidents are *strategic research sites* for those who want to study issues of safety and risk, of reliability and vulnerability of complex technological systems.

As sites for collective and public learning from these failures, public inquiries and other post-accident investigations that are conducted in the immediate aftermath of a large scale accident have their limitations and pitfalls. First, many post-accident investigations start from the assumption that a fundamental error or a serious violation of safety regulations must have been ‘committed’. Or that there was a random mechanical or technical failure, also a deviation from some ideal state. Without such an error, breach of regulations or random technical failure the system would have continued to perform reliably. Much of the investigative efforts go into the *localization* and *fixing* of the error or deviation. This basic assumption is rarely questioned. It is rarely questioned because, as a secondary process, the investigation starts from disastrous *outcomes*. The paradoxical conclusion that, in the primary process of the work, there was no error, or that the failure resulted from doing the job as good as possible, does not easily emerge. Errors and other deviations are reconstructed in the secondary process of the post-accident investigation. Often it is not at all evident that they could have been recognized as 'contributing causes' – to an outcome that has not yet occurred - in and from the perspective of the primary process of work.

Second, in large scale accidents involving complex technological systems the damages sustained are grave. Human lives are lost. Invested capital is lost. The system is no longer available for the production and delivery of goods or the provision of services. Legally binding regularity requirements can no longer be met. Issues of criminal and civil liability dominate the aftermath of large scale accidents. Public inquiries and other post-accident investigations can not be divorced from this process. Even when they present themselves as pure fact-finding missions, the attribution of causality that they perform – through the reconstruction, localization and fixing of errors and other deviations - is intimately linked with the attribution and distribution of responsibility and liability. However, accident investigation reports do not 'conclude' liability issues. These may continue for years after the accident, keeping information under lock and hampering further public understanding and learning from large scale accidents.

For these reasons it may be worthwhile to revisit large scale accidents a couple of years later, when liability issues have been settled, when reports that were confidential have been released and become publicly available. And when people involved in the primary process can think and talk about their work without legal restrictions. The general questions that we should put to these accidents are: Why were the organizations that operated the complex technological systems involved not able to maintain performative closure? What in the dynamics of the system made them loose that ability to achieve and maintain functional and technical integrity under the specific circumstances leading up to the accident? In other words, what made them *vulnerable*? The term *vulnerability*, as it is used here, refers to a reduced ability to anticipate, resist, cope with or recover from 'events' that threaten the achievement or maintenance of performative closure.

This study puts these questions about the vulnerability of complex technological systems to the loss of the gravity base structure (GBS) for Sleipner A in 1991. In August 1991 Norwegian Contractors (NC) lost the concrete GBS for the Sleipner A Condeep-platform while it was being prepared for deck mating. Fortunately no human lives were lost and there was no environmental damage. Hence, there was no *public* inquiry into the accident. Both Statoil and Norwegian Contractors established corporate accident investigation committees. Although there was no wreck to be recovered for the purpose of technical investigations, the immediate causal chain of events has been reconstructed in numerical models and sinking scenarios and in full-scale models of sections of the structure. This work put tricell geometry and the shape, dimensions and placement of reinforcement steel in these areas into focus.

Soon after the accident both NC's and Statoil's conclusions gravitated towards 'fundamental errors' made by NC's design team in the global analysis for the platform. The direction and focus of these early conclusions were due to two factors: a) both NC's and Statoil's primary interest in finding the *immediate* causes of the loss in order to be able to correct them and build a new platform, Sleipner A2, as soon as possible, and b) an early decision in legal circles to focus the liability case on Aker Maritime owned Norwegian Contractors - the main contractor on Sleipner – and to exempt all subcontractors from financial liability.

The civil liability procedures dominated investigations into the Sleipner A GBS Loss for 6 years, until finally the liability issue was settled out of court in 1997. By that time, however, Norwegian Contractors had been dismantled and the 'fundamental error' conclusion had frozen into the few records that were publicly available. However, Sleipner A was number 12 in a series of concrete gravity base structures that the company had built since the middle of the 1970. On several accounts Sleipner A was a moderate one. NC had developed a reputation of being able to deliver these mega-construction projects on time and on site. In spite of the early ‘fundamental error’ conclusions, the question of why a top entrepreneurial company like Norwegian Contractors failed on a relatively moderate assignment like Sleipner A is still poorly understood, at least as far as publicly available records and accounts are concerned. This is the question that is of central concern here. It is a question that asks for a better (public) understanding of the processes that were behind, or better, that produced the set of ‘immediate causes’ as they have been reconstructed after the accident in 1991. It is a question that asks for the ways in which Norwegian Contractors had become vulnerable.

Although I have worked in complex technological systems, and have studied several others, I am not an engineer. Several of the engineers that were involved in the design of Sleipner A were very patient in explaining the engineering issues to me in extended interviews. The presentation of these engineering issues in this study reflects my understanding of them. Furthermore, as a matter of presentation in a written paper alone, some degree of simplification is inevitable. I am responsible for any ´errors´ or oversimplification that remain. The text of a study must be concluded at some point because it must be sent to the printer. The empirical research may continue, however. There are some empirical questions that I have not yet been able to establish. I am flagging them in footnotes. I hope to fill out these gaps in later versions of the study. The most important message of this study, however, is in the structure and conclusions of the narrative of the Sleipner A GBS loss as I am telling it. A narrative that in its conclusions runs counter to the ´fundamental error´ account that has frozen into what is available in terms of public records, into stories as they are told and retold until today and into the teaching of new generations of Norwegian engineers at technical universities. Final, definite accounts do not exists. Alternative accounts are always possible. Learning occurs in the active confrontation of and discussion among alternative accounts. Or, as Kristian Bredesen puts it in his book on the 1999 MS Sleipner accident at Store Bloksen: ‘The best thing about a book is not its contents but the thoughts that it shapes’.

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Ger Wackers

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Chapter 1

The 1991 Sleipner A GBS loss

1.1. The unimaginable happens

On August 23, 1991, seismological stations in southern Norway registered a vibration with a force of 3 on Richter’s scale. Investigations identified the cause of the vibration: a concrete offshore production platform (Sleipner A), that was under construction and being prepared for ‘deck mating’, sprang a leak, capsized, imploded on its way down and hit the seafloor as a mass of rubble and bend reinforcement steel in Gandsfjorden near Stavanger (Holand 1997). Norwegian Contractors (NC), was building Sleipner A at its construction site at Hinna in Stavanger, for Statoil, the Norwegian state oil company.

Alert Gaard, Statoil’s engineering manager on the Sleipner A project – being in charge in the absence (holiday) of the project director – received a phone call from the company’s site representative at Hinna ‘with the unbelievable news that what never could happen had happened’ (Gaard 1992: 3). The impact of concrete and steel did not only rock the seafloor, it also rocked the reputation, if not the confidence, of one of Norway’s top entrepreneurial and construction firms in the offshore industry. For Statoil the loss of Sleipner implied a considerable set back in the development of the Sleipner gas field. Sleipner A was to be the first production installation on the field and Statoil was committed to start production on the first of October 1993. The loss of invested capital was so huge that any liability claim, when awarded, could easily topple not only Norwegian Contractors, but also Aker Maritime, the major Norwegian offshore engineering company that was the full owner of NC. Prior to this unimaginable event Norwegian Contractors had never lost a platform. To the contrary, over the years, they had developed a high degree of confidence in their ability to deliver these huge structures on-site and on time.

1.2. Solutions in concrete

Since the early days of oil and gas field developments in the North Sea offshore industry (in the early 1970s) Norwegian Contractors had offered 'solutions in concrete' to oil companies.[1] NC's reputation was based on their ability to produce and deliver on-site and on-time so-called Condeep platforms: the load bearing and supporting base structure of a fixed platform standing on the seafloor. A typical Condeep consisted of a set of cylindrical cells constituting the foot of the structure, some of which – varying from 1 – 4 in number – were elongated into tall shafts extending above the sea water level and supporting the topside structure with decks, installations and accommodation[2]. As a company Norwegian Contractors developed a self-aware confidence in their ability to build these huge concrete structures and in their capacity to tackle and solve any major problem that might arise in the process.

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[1] The building of the Ekofisk tank in 1973, on a contract for a French firm, C.G. Doris, established concrete as a building material offshore and the partnership of three Norwegian entrepreneurial firms (AF Høyer Ellefsen, F. Selmer and Thor Furuholmen) that formed Norwegian Contractors as a reliable partner (Steen 1993).

[2] The basic concept of the Condeep platforms is as simple as it is ingenious. The large cylindrical cells of the GBS displace so much water to generate sufficient upward pressure to support the weight of the concrete structure itself and the weight of the topside installations. The bottoms were constructed in a dry-dock, towed out to deep water after which the cells and shafts were built in a continuous process of slip forming while being afloat; that is, concrete structures as high as the Eiffel Tower. After deck mating the platforms were towed out to the destined site in the North Sea, put on the sea floor, and hooked up to oil or gas wells. In the summer of 1975 NC had four of these mega-projects under various phases of construction simultaneously: Beryl A, Brent B, Statfjord A and Brent D. They would accomplish the same feat again between 1993 and 1995. In 1988 Norwegian Contractors was awarded the international Offshore Petroleum Conference's Distinguished Achievement Award for their contributions in advancing the design and fabrication of concrete offshore structures.

Sleipner A was number 12 in the series of ‘gravity[3] base structures’ (GBS) of the Condeep-type built by Norwegian Contractors. And it was a relatively small one. During the 1980’s NC had built the Gullfaks-series, with 262 meter high Gullfaks C (standing in 200 meters deep water) being the largest Condeep ever built, that is in terms of volume of concrete. Construction of the tallest one, 369 meters high Troll (to stand in 300 meters deep water) had just started in July 1991.[4] Sleipner A was designed to stand in 89 meters of water and the concrete GBS (to the top of the four shafts) would be 110 meters high.

1.3. Research question and up front conclusion:

No Error!

Why did a top firm like Norwegian Contractors – that was good at what it was doing - fail on a moderate assignment like Sleipner A? This will be the leading research question throughout this study.

I will offer my main conclusion up front and use the remainder of the study to make good on that claim: There was NO ERROR! NC’s failing on this moderate assignment resulted from doing the job as good as possible. NC’s design team did not violate a set of well-established, deterministic rules, that is rules providing detailed instructions on how the job is to be performed; deterministic rules that would provide an unambiguous frame of reference defining violations or transgressions of these rules as errors. Rules and regulations underlying the design and engineering of constructions in concrete for offshore applications were not deterministic. They constrained possibilities, but also delineated a space for further adaptive improvement and optimization, meeting local and emergent criteria for good work and resonating positively with performance criteria in other parts of the company and in other companies. NC’s design team

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[3] The word gravity here implies that these platforms, after on site installation, stand directly on the seafloor being stabilized by their own weight, without any additional support structures (Hjelde 1979: 4).

[4] The Shell-NC contract for Troll, signed on March 21 1991, was at the time Norway’s largest industrial contract ever (Steen 1993: 134).

optimized the design according to local standards and sound engineering judgment. Specific design solutions passed through various forms and levels of (ISO 9000 certified) quality checks and external revisions, until they were put to the final test by the physical environment of the deep water of Gandsfjorden.

This conclusion implies that I am not subscribing to the explanation saying that NC failed on Sleipner A because they assigned a B-team of not-their-best to the job – the A-team being drawn to the much more prestigious, because tallest-ever, Troll-project, for which the contract had been signed half a year before the Sleipner contract. Neither do I subscribe to hubristic explanations saying that NC's failure was due to misplaced confidence in their own abilities and that they did not take this project, moderate in terms of size and water depth when measured against the volume of concrete in Gullfaks C and the height of Troll, serious enough. NC's self-confidence was grounded in a historical record of completing and delivering eleven of these mega-construction projects on time and on site – twelve if we include the Ekofisk tank.

However, my conclusion runs counter to the main conclusions of published engineering accounts speaking of 'fundamental errors' in the global analysis and in the detailing of reinforcement steel. The 'discrepancy' in conclusions has to do with a) features of the accident-investigation process and b) with my own (re)framing of the design process in terms of an adaptive search process; of networks of organizations like Norwegian Contractors and its commissioning companies and subcontractors, in terms of complex adaptive systems. I will address these issues in chapters two and three respectively, before moving on to a detailed analysis of the Sleipner A design process.

This study is part of a larger project on issues of reliability and vulnerability in complex technological systems in the North Sea offshore industry. Accidents provide important 'strategic research sites' (Bijker et al. 1987) where these issues are researchable. In a number of case studies I am looking for patterns of mechanisms that can help us in understanding unexpected failures in complex technological systems (Wackers and Kørte 2003). From these case studies we might be able to derive alternative approaches to accident investigations and to proactive monitoring tools aiming for condition oriented ‘vulnerability profiling’, rather than consequence oriented and event based quantitative risk analysis.

1.4. Sources

Because no human lives were lost in the SLA GBS Loss and because there was no environmental damage, there was no ‘public inquiry’ into the accident. Hence there is no public inquiry report. There are only a few published accounts in technical engineering journals. The analysis and account of the Sleipner A GBS Loss in this study is based on a variety of sources. First, there is a set of technical reports commissioned by Statoil from SINTEF. These reports were made publicly available in 1997. Second, I have been given access to company internal accident investigation reports produced by Norwegian Contractors and Statoil respectively in the weeks and months following the accident. I have also been given access to a report compiled in 1995 by the Sleipner A design team in response to many of the accusations directed at them in the civil liability procedures. Finally, I have conducted a series of interviews with (former) Norwegian Contractor engineers involved in the design and construction of Sleipner A.

1.5. Structure of the study

Chapter 2 describes some characteristics of the accident investigation process into the Sleipner A GBS Loss. These features explain the focal nature of the fundamental error type of conclusion, limiting the *location of the problem* to NC’s design team and the *time of the problem* to a couple of months in an extended process that covered several years. The chapter introduces an important distinction between primary (every day work) and secondary (post-accident investigation) processes. In a sense, the chapter clears the way for alternative accounts. This study makes a conscious effort to focus on the primary processes of the design and engineering work.

Chapter 3, then, proceeds by introducing a conceptual framework that allows us to describe and analyze the primary process of the Sleipner A design and engineering work in terms of an adaptive, optimizing up-hill search on a fitness landscape. The units of analysis are *adaptive performance systems* and the achievement of *performative closure* (in task or goal accomplishment) is an important feature with regard to *selection* processes. This is a conceptual framework that can be applied across levels, or at different levels of aggregation. Chapter 3 illustrates this perspective by recounting and reframing in these terms the history of Norwegian Contractors at the level of the *company*. In doing so, the chapter ‘unfreezes’ the focal fundamental error type of conclusion, expanding the space of processes and mechanisms that might be of relevance for a proper understanding of the Sleipner A GBS Loss. Simultaneously the chapter ‘sets the stage’ for the subsequent chapters that apply this perspective ‘one level lower than the level of the company’, to the design work performed by NC’s design team and the engineering work performed by its subcontractors.

Chapters 4, 5 and 6 take issue with a number of features in which Sleipner A was different from previous Condeep-projects. These are the adaptive changes aiming at improved performance that come into focus when applying the conceptual framework introduced in Chapter 3. Chapter 4 covers some adaptive changes that were made before the contract between Statoil and Norwegian Contractors was signed. Chapter 5 covers issues that have to do with the global analysis (design), whereas chapter 6 covers adaptive changes in the translation of the outcomes of the global analysis into dimensions and placement of reinforcement steel, drawings and material lists (engineering).

Chapter 7 tries to develop some of the lessons that can be learned from this account of the Sleipner A GBS Loss.

Chapter 2
Avoiding post-accident optical effects

NO ERROR! Failure through optimization! A paradoxical conclusion, indeed, that runs counter to accounts that speak of fundamental errors that have been committed. To clear the way for an alternative account we must address some features of the accident investigation process through which these ‘fundamental error’ conclusions were established.

2.1. Primary and secondary processes

First of all it is important to recognize the distinction between primary and secondary processes. In constructivist science and technology studies this is a familiar notion (Latour 1979: 134). Primary processes are the actual, real-time work processes prior to the accident, as they are performed and experienced (or lived) by the engineers and construction workers in the flow of the work. Secondary processes are the activities of the post-accident investigations looking for the causes of the failure and loss. These activities involve a different group of people who were not involved in the primary process. Independent accident investigation committees are set up. National and international experts and consultants are brought in to scrutinize the primary process and identify the errors constituting the (immediate) causes of the failure. Once the errors have been ‘dis- or uncovered’ it seems as if they have always been there, committed but undiscovered in the flow of work. When the ‘errors’ are deemed to be ‘fundamental’ there often is amazement: How can they – the primary process people – not have seen this? However, when you try to ‘look through the eyes’ of the people involved in the primary process the ‘errors’ are not at all ‘easy to see’: there are NO ERRORS, not in the primary process. The errors are reconstructed in the secondary processes of post-accident investigations.

Of course, the analysis and account in this chapter also builds on secondary process work, or rather third process work. In a methodological sense, this account self-consciously puts the primary process into focus. However, from our position, more then 10 years after the SLA GBS loss, we can also consider the post-accident investigations performed immediately after the accident.

2.2. Identifying the immediate causal mechanism

On August 23, 1991, 22 people were on the platform when the first bang was heard and water rushed uncontrolled into one of the four shafts (D3). Ballast pumps were started immediately but their capacity was not sufficient. The people were evacuated and it took 18 minutes for the platform to capsize and sink. Video images from a remotely controlled submarine sent down showed a pile of concrete rubble and bent reinforcement steel, partially buried in the sand on the seafloor. The structure imploded on its way down. There was nothing to recover for technical investigations. Both the main contractor, NC, and the owner, Statoil established corporate accident investigation committees.[5]

Bernt Jakobsen, one of NC's senior engineers, recalled a session with NC's accident investigation committee in which they were presented with the geometry and the design details of the tricells: the triangular spaces (interstices) that arise when you put circular cylinders together.[6] Knowing about the outcome, and being presented - in the context of an accident investigation - with the tricell's geometry, he recognized that the tricell corner provided negative supports for the tricell/shaft walls, given the open connection with the ambient water through the hole in the top-domes of the tricells. He also recognized the special demands a negative support situation put

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[5] Because no lives were lost and because there was no environmental damage, no 'public inquiry' was conducted. Hence, for the 1991 SLA GBS Loss there is no public inquiry report.

[6] Until then the committee had considered all possible causes of the leak, like for example sites in which large tubes and risers penetrated the concrete walls and domes of the shafts.

on the design and placement of reinforcements in the corners. This focused the committee’s efforts on the tricells. Recalculations performed in Trondheim by SINTEF - using different software packages - gave results that were significantly higher than the calculations performed by NC’s design team. Or conversely, NC’s results underestimated shear forces with some 43 %. SINTEF’s results where confirmed in full-scale tests in a construction testing facility in Borås, in Sweden (Tomaszewicz: 1997). On the basis of eyewitness accounts and numerical simulations several sinking scenarios were developed, making assumptions about the most probable site and size of the leak (Oldervik 1997).

This work resulted in the establishment of a probable causal mechanism: when the pressure difference across the tri-cell/D3-shaft wall exceeded a critical point - during the controlled submergence of the platform in preparation of deck-mating – one or more cracks formed that propagated around the reinforcement steel through the whole thickness of the wall, allowing water from the tricells, that were in open connection with the sea, to rush in.

The two accident investigation committees were confident that they had identified the (immediate) causal mechanism of the loss. I will not take issue with these technical reconstructions and investigations. In my analysis I will accept these conclusions as a matter of fact.

2.3 Easy to see?

From these investigations it was also concluded that NC’s design team had made some fundamental errors in the global (finite element) analysis – that is, in the calculation of stresses and forces – of the platform, resulting in errors in the translation of these forces into size, shape, number and placement of reinforcement steel. This is the account that you will find in several of the technical papers on the Sleipner A GBS Loss either published or presented at various conferences (Gaard 1992; Jakobsen 1994; Jakobsen & Rosendahl 1994; Collins et al. 1997). Gudmestad, Aas Warland and Stead (1993: 6) wrote:

> *It was documented that this accident was caused by:*
> *- error in the finite element analysis;*
> *- error in reinforcement detailing.*

In an interview, a professor in marine engineering at the technical university in Trondheim, expressed the severity of the error like this: 'Any second year civil engineering student with a slide ruler checking the outcomes of the calculations would have seen that they couldn't be right!' But is it? Is it that easy to see? The answer is YES when you are confronted with the failure and after the secondary process has (re)constructed the error for you. The answer is NO when you look at the primary processes: NO ERROR.

2.4. Optical effects

The post-accident focal emphasis on these 'errors' in a design and engineering process that was lengthy in time and spread over many sites in a network of companies and consultants, was the result of an 'optical effect'. The direction and focus of these early conclusions were due to two factors.

First, both NC's and Statoil's primary interest was in finding the *immediate* causes of the loss in order to be able to correct them and build a new platform, Sleipner A2, as soon as possible. Statoil was committed by contracts with large customers to start production of and deliver natural gas from the Sleipner field by the 1st of October 1993. These contractual obligations were not suspended because of the loss of the gravity base structure of the first production platform for the field. Redoing the whole design and engineering process would take too much time. Rebuilding the platform using basically the same design was preferable, that is, if local, specific errors could be identified and corrected.

Second, an early decision was made in legal circles to focus the civil liability case on Aker Maritime owned Norwegian Contractors – the main contractor on Sleipner – and to exempt all subcontractors from financial liability. One of the owners of the Sleipner field license had no insurance coverage for the capital investments required for the development of the field. The only way for this oil company to recover some of the invested capital lost in the accident was through a civil liability procedure.[7] The size of the claim was such that the only company from which such an amount could be reclaimed was Aker Maritime. Even for Aker Maritime an obligation to pay the full amount of the claim could well have caused bankruptcy of the company. The civil liability procedures dominated investigations into the Sleipner A GBS Loss for 6 years, until finally the liability issue was settled out of court in 1997.

These two factors defined the nature and the locus of the problem: they brought the design work performed by NC's SLA-design team during a couple of months in the fall of 1988 and winter 1989 into focus, identifying it as the site and time of the problem, simultaneously reducing and simplifying it by fixing the cause of the failure in and to the work performed in the global analysis. As a result of the typically dual effect of tracing the boundaries of a problem definition (Callon 1980), they defined a large part of the platform production process as not-relevant for the understanding of why Norwegian Contractors failed on a moderate assignment like Sleipner A. An important task in this study is to enlarge the scope of relevant mechanisms and processes and to bring into view again what has been forgotten or suppressed – at least in the publicly available accounts - in and through the reductionist and simplifying 'fundamental error' explanations (Law & Mol 2002: 3).

As is often the case, financial liability procedures put a legal filter on information that is released to the public domain. Company lawyers are adamant about any information or statement that could be interpreted as an admission of liability. Early publications in engineering journals had to be approved by Statoil. SINTEF's series of technical reports remained classified until the out-of-court settlement of the liability issue in 1997. As a company Norwegian Contractors was dismantled two years earlier, in 1995, that is: after the completion of Sleipner A2, Troll, Draugen and Heidrun – between 1992 and 1995 NC had four of these mega-projects under construction

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[7] Police investigations concluded that there was no evidence to suggest some form of criminal negligence that would warrant prosecution according to criminal law.

simultaneously. After the out-of-court settlement of the liability case the more fundamental causes of NC’s failure have not been re-addressed. In public domain sources the ‘fundamental error’ conclusion remains the standard account. It is this account that this study takes issue with.

2.5. Shifting perspective

In order to understand how NC failed by doing a good job as possible we will have to avoid the specific optical effects of the secondary, post-accident process investigations and look at the primary processes. To do so we will need to enlarge the scope and shift our perspective with a different set of conceptual tools to help us recognize the relevant processes and mechanisms that have been suppressed and forgotten. These conceptual tools should allow us to appreciate that:

1) each Condeep-platform is a unique product that has to be adapted to a) the specific natural seafloor characteristics and water depths of its intended site, including the forces of highest waves or fiercest storms that the platform must resist during its lifetime, b) the specifics of the installations required for production, processing of and storage of the gas or oil in the reservoir, together determining the weight of the topside, c) the economic climate (oil and gas prices, profit margins, cash flow, overall field development costs), and d) the time left to preset and intended start of production.
2) multiple companies and consultants are involved in the process, performing different roles and tasks over an extended period of time, having different responsibilities.

I found concepts meeting these requirements in recent work in complexity theory. I will introduce them briefly in the next chapter - while simultaneously enlarging the scope of relevant processes - and then use them in the account of the Sleipner A design process in subsequent chapters.

Chapter 3

Adaptation, interaction and culture

This chapter has a dual purpose. First, it will introduce a core set of concepts – drawn from the field of complexity theory - that will allow us to recognize the adaptive and emergent processes that have been suppressed in the ‘fundamental error’ accounts that are publicly available. Second, it will take steps in ‘enlarging the scope’ through the demonstration of the heuristic value of these concepts with examples from Norwegian Contractor’s history and organizational structure.

Complexity theory[8] is a theory of the emergence of global patterns – or forms or structures – from local interactions. Originating in mathematics and theoretical physics (Waldrop 1992) it is now translated into a wide range of disciplines, from biology and brain research (Solé & Goodwin 2000) to sociology, organizational theory, business and management studies (Eve et al. 1997; Marion 1999; Sherman and Schultz 1998; Stacey 2000; Streatfield 2001). Together complexity theorists cover a wide range of phenomena, ranging from morphogenesis, that is the emergence of (anatomical) forms in biological organisms (Goodwin 1994), the origin of life and of ecosystems (Kauffman 1993; 1995), synchronization in biological systems (oscillators) as well as physical and social systems (Strogatz 2003) to the exploration of emergent behavior in agent-based (computer) models (Holland 1994: 1998) and in real-world, evolving networks (Barabási 2002). Complexity theorists are fascinated by self-organizing, enduring or transient patterns, whether they are ant hills, the human immune system, cities or other forms of social organization, that is, in forms of order that do not require a central, coordinating agent neither to produce nor to explain their global

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[8] Complexity theory is not a single or unified theory. It is rather a set of theoretical ideas and approaches that share a similar outlook on and interest in the dynamics of systems exhibiting emergent behaviour. For reasons of convenience, however, I will use the term complexity theory in the singular. Other authors speak about complexity thinking or non-linear thinking.

behavior (Johnson 2001). This is not to deny that in social systems and organizations human actors have intentions, motives or strategies, however, these are not sufficient to explain the global behavior of the system. Complexity theory is a theory of complex adaptive systems (CAS), comprised of individual (adaptive) agents; agents that take different shapes, depending of the level of aggregation and description. From this body of work we can derive several concepts that can be fruitfully applied in the analysis of the Sleipner A design process.

3.1. Landscapes

Landscapes of valleys, ridges, foothills and mountains are useful images to visualize and think about the dynamic behavior of complex adaptive systems (Abraham and Shaw 1992: 47 ff.). As a geometric model, the landscape represents an abstract space of all possible states that a system can be in. The actual state of a system represents a point on that virtual landscape. Adaptive changes in the system's state trace a trajectory on the surface of the landscape.

Basically, landscapes come in two forms: as energy landscapes and as fitness landscapes. Energy landscapes have their origin in physics. The valleys represent low energy states. The ridges and high-country hills represent high-energy states, separating basins of lower energy. The slopes, or better, the steepness of the slopes, represent energy gradients. In its most general formulation, energy is 'some kind of function that is minimized through the dynamics' (Solé and Goodwin 2000: 126) We can think of energy in terms of costs, effort or work. An organization settling into a routine mode of production can be seen as moving down along the slope (gradient) of a valley towards an energy minimum where it can perform its tasks effectively and efficiently, that is, for the lowest costs and communicative effort possible. We can also think of disciplines as occupying different valleys in an energy landscape. On the basis of shared conventions, common understanding and a specialized, technical vocabulary communication within a discipline requires little effort, whereas communication across disciplinary boundaries (the high energy ridges) requires a considerable amount of effort. Energy landscapes are used in several specialized fields making extensive use of computer modeling, for example in pattern recognition by neural networks. The process of pattern recognition (of a corrupted pattern) is visualized as a downhill movement to the bottom of energy valleys representing a given memory state (previously learned pattern) (Solé & Goodwin 2000: 127-8). In a quite different field, Axelrod (1997: 72 ff.), a political scientist, uses a landscape theory (of aggregation) in his work on the formation of coalitions, alliances and organizational structures.

Fitness landscapes have their origin in theoretical, evolutionary biology. In fitness landscapes the vertical dimension represents higher or lower fitness. Fitness is low in the valleys and high on the ridges and peaks. Biologists like Wright and Jacob thought of the evolution of life as adaptation through small changes involving a local search in the space of possibilities. The image is one of local hill climbing via fitter mutants toward some local or global optimum in a fitness landscape (Kauffman 1993: 33). But not all changes are beneficial. Some result in lower fitness and a downhill move on the surface of the landscape. Fitness landscapes also provide a framework for thinking about the difference between exploitation and exploration (March 1991). Exploitation refers to a reliance on features and ways of doing that proved to be successful and improving on them to climb further towards, or to stay on the top of the current hill. Exploration, then, refers to changes that perhaps result in lower fitness in the short run but that allows searches in the landscape for fitness optima that might be higher than the current one. Radical and risky innovations constitute ‘long jumps’ across the fitness landscape (Kauffman 1995: 193).

Fitness landscapes are not static or fixed. They are dynamic and flexible. The number, size, shape and position of peaks and valleys depend on the adaptive strategies of agents in the same field. The emergence or entrance of a competitor produces changes in the fitness landscape. Dramatic events like the OPEC-induced 1973 energy crisis warp the landscape altogether, causing severe crisis in one place and creating new opportunities in another.

It is easy to see why thinking in terms of complexity and fitness landscapes should appeal to scholars in organization theory and management (Stacey 2000: 291 ff.; Sherman & Schultz 1998). Innovative companies seem to be the archetypical complex adaptive systems in the social and economic realm. In highly competitive markets, with shrinking product life cycles and decreasing times to market, ‘the businesses that succeed are those that are first within the industry to see an adjacent opportunity and act upon it’ (Sherman & Schultz 1998: 23). The primary interest is in ways to exploit insights in complex, emergent behavior to devise new managerial strategies for the benefit of an organization’s competitiveness, profitability and survivability, that is to ‘harness complexity’ (Axelrod & Cohen 2000). Little attention, however, has been given to the ‘downside’ of this adaptive behavior, that is, to the ways in which adaptive search strategies that aim for improvement also induce system vulnerabilities.[9]

The notion of fitness landscapes can be used across levels of aggregation. In subsequent chapters of this study my focus will be on the level of NC’s SLA-design team, one level of aggregation lower than the level of NC as a company. Before moving down, let me use an overview of the history of Norwegian Contractors to illustrate the heuristic value of the notion of fitness landscapes, while, at the same time, taking a first step to enlarge the scope of relevant processes leading up to the 1991 loss of the Sleipner A GBS.

3.2. Norwegian Contractors’ fitness landscape

3.2.1. Emerging landscape of opportunities

The discovery, in 1959, of a large natural gas field near Slochteren in the Netherlands, followed in subsequent years by investigations of the geological layers harboring this reservoir - layers that extended into the floor of the North Sea - established the North Sea as a field of opportunities and possibilities for oil companies and supplier

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[9] Barabási, a physicist exploring the properties and structure of real-world evolving networks, argues that networks with a ‘scale-free topology’, like for example the internet, have a high tolerance (robustness) for random, local failures in combination with a high vulnerability to coordinated attacks on the network’s most connected hubs (Barabási 2002).

industries alike. However, a decade of exploration drilling and dry wells elapsed before the discovery of the Ekofisk field in 1969 by US based Phillips Petroleum Company.

In the early 1970s a number of (f)actors shaped the fitness landscape on which three Norwegian entrepreneurial firms started their adaptive search.

The Norwegian government – having resisted Phillips Petroleum's 'bluff' request for a concession for the whole Norwegian continental shelf – made the granting of concessions conditional on the involvement of Norwegian firms and suppliers, so that the capital investments necessary for offshore field development would benefit Norwegian national and regional economies and create jobs (Ryggvik 1997).

The foreign oil companies dominating early production in the North Sea – following the discovery of the Ekofisk field in 1969 - did not bring ready-made field development solutions to the area. They had two decades offshore experience in the shallow water of the Mexican Gulf. The North Sea, although still a shallow sea allowing fixed platforms, was deeper and the climate was much harsher. Conventional technologies did not suffice to guarantee sustained safe and regular production; i.e. on-site storage facilities were necessary for sustained production when bad weather prohibited tankers to load oil. New technological solutions had to be developed. The harsh climate made construction work and heavy lifting operations on offshore-sites difficult and expensive. The Norwegian fjords provided unique sheltered, but deep-water construction sites, with on-land storage facilities and mechanical workshops only a stone cast away (Olsen & Engen 1997).

The unilateral action of the Organisation of Petroleum Exporting Countries (OPEC) in 1973 to increase the 'tax reference price' with 70% and to reduce production rates produced a fourfold increase of an already rising marked price for oil and accelerated the rate of field development in the North Sea area (Hanisch & Nerheim 1992:422 ff.). Speed of delivery was a crucial factor. Phillips Petroleum wanted to build a large oil storage facility on the Ekofisk field.

3.2.2. Adjacent opportunities

Three Norwegian entrepreneurial firms, A/F Høyer Ellefsen, F. Selmer and Thor Furuholmen, recognized in this specific configurations of (f)actors an adjacent opportunity[10] to claim for themselves a place in this emerging and expanding field of the North Sea offshore industry. They joint forces in a working partnership and asserted under the name of Norwegian Contractor's their ability to deliver a storage facility for Phillip's Ekofisk-field in concrete faster than any alternative solution. This tipped the scale in favor of a solution in concrete. The contract was awarded to a French firm, C.G. Dorris, with Norwegian Contractors as subcontractors for the actual construction and delivery of the Ekofisk-tank (Olsen & Engen: 1997: 116). Building the tank as a floating structure in the fjord near Stavanger, the partnership of three Norwegian entrepreneurs delivered the tank *on site* on July 1, 1973 (Hanisch & Nerheim 1992: 201 ff.).

For Norway and for a range of Norwegian companies the adventure of offshore oil and gas production in the North Sea had started for real. Expectations were high. It would be a quickly expanding though dynamic market with high profit margins. The partnership that constituted Norwegian Contractors started on an adaptive search for an optimal position and performance in the emerging market. On the Ekofisk-tank NC had been a subcontractor for the French company C.G. Doris who had designed and engineered the tank. On the basis of their 'own' (patented) Condeep-concept NC now entered into the bidding process for production platforms for new fields both on the Norwegian and British continental shelf (Brent, Beryl, Statfjord). And they were successful. In the fall of 1974 and winter 1975 Norwegian Contractors had six platforms in concrete under construction at two different construction sites in Åndalsnes and in Stavanger (Beryl A, Brent B, Statfjord A, Brent D, CDP-1 for the

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[10] Like in a play of chess, an adjacent opportunity is a 'possible move', made possible by the emergence of a specific configuration of pieces on the board. While excluding a range of moves that are not or no longer possible, the emergent configuration does not determine the ones that are possible.

Frigg field, and TCP-2)[11] (Steen 1993: 21 ff.) With regard to fixed production platform solutions the fitness landscape now had at least two fitness hills, one for solutions in steel and one for solutions in concrete. The group of licensees (oil companies) looking for optimal field development solutions would have to make an early decision for steel or for concrete; a choice to which they would be increasingly committed as the work progressed (lock-in).

3.2.3. Uphill search strategy: developing turn key capability

The livelihood of a company depends on the regularity with which it can generate revenues. Being dependent on a few, although very large projects made Norwegian Contractors vulnerable. NC sought to improve its economic fitness along two different lines. The first strategy was through diversification, or in landscape terms, the exploration of distant fitness hills. At the end of the 1970s and in the early 1980s NC looked for other applications of concrete in the offshore industry. This was the decade of the construction of the large pipes for the transportation of oil and gas directly from the fields to on-shore installations. These steel pipes were coated with a layer of concrete. Forming a partnership with Bredero Price International (Bredero Norwegian Constractors = BNC) NC won a contract for the coating of the Statpipe. NC also engaged itself in two other companies, Inocean and Deepocean, devoted to subsea construction and subsea engineering (Steen 1993: 54 ff.).

The second strategy amounted to climbing the Condeep-fitness hill further. NC’s 1970s contracts on concrete platforms were partial contracts. The oil companies that acted as operators for a field – on behalf of the group of licensees – held the discretionary power to award contracts for various parts of the production process to different companies. NC’s core competence, that it set out with in the early

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[11] In this same period contracts for six other platforms in concrete were awarded to (partnerships of) companies outside of Norway, in Great Britain, the Netherlands and France. After this first wave of concrete platforms in the 1970s several years elapsed before another one was commissioned. Market conditions had changed by then and in the early 1980s Norwegian Contractors was alone (Steen 1993: 34).

1970s on its adaptive search, was in building in concrete, not in designing and engineering of concrete constructions, not in mechanical engineering, not in maritime operations.[12]

Through their 1970s projects Norwegian Constractors developed expertise in all these areas. Over the years NC developed a high in-house competence for marine operations: deck mating and the towing to and installation of Condeep-platforms on their offshore-site. The TCP-2 platform was the first platform in which NC was responsible for the (marine) deck mating operation.

Mechanical engineering on a concrete gravity base structures falls into two parts: 1) the tubing, pumps and (computer) equipment that are necessary for the ballasting and balancing operations through the various phases of the platform’s construction (Contractors Mechanical Outfitting = CMO), and 2) the tubing and equipment required in the process of oil and gas productions, called Main Mechanical Outfitting (MMO), connecting the topside installations with the wells on the seafloor. Statfjord B was the first platform for which NC got the contract for the CMO. Later, during the 1980s NC also landed contracts for the MMO for Troll and Draugen (Steen 1993: 58 ff.). In 1988 Norwegian Contractors established a separate mechanical engineering division that also competed for not-offshore related, land based mechanical engineering contracts. In terms of fitness landscapes this latter move represents a process of exploration of distant fitness hills again.

Over the years Norwegian Contractors pursued an uphill search strategy aimed at developing ‘turn key capability’, that is the ability to

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[12] In the specific context of the production of platforms I will use the word design to refer to work entailed in modelling the platform and solving the mathematical equations representing forces, stresses and tensions in the concrete structure under various phases of its fabrication, use and possible impacts from ships, storms and earthquakes. In the same context I will use the word engineering to the work entailed in the translation of the design output into dimensions and placement of reinforcement steel, drawings and lists of materials to be used on the construction site. The word construction will refer to the actual building process. Marine operations refers to the towing out of a platform to its offshore site and installation to its placement on the seafloor, hooking it up to oil or gas wells and pipelines, preparing the platform for production.

offer complete solutions under one contract to the commissioning oil companies. We can subsume NC's investments in the development of in-house expertise in global or finite element analysis under the same sustained uphill search strategy.

For Condeep-projects in the 1970s en 1980s, the global or finite element analysis and the engineering were contracted out. Computas, a DNV company, did the global analysis (GA) until 1984. Thereafter Veritec did the GA – the technical and consultancy branch of Det Norske Veritas (Andersen & Collett 1989: 385) in Høvik near Oslo. The engineering was done by Dr tech Olav Olsen, an engineering firm located very close to NC's Stabekk offices in Oslo. While contracting out the global analysis for the platforms-to-be-build to Computas/Veritec, over the years NC performed 10 large GA-studies in house. Furthermore, NC developed specific software that would allow them to automate the input of data representing the many different load situations (NC 1995: 10).

3.2.4. Changing landscape

NC performed well in this fitness landscape. In the 1980s they achieved a monopoly position for concrete offshore constructions in the North Sea. In the second half of the 1980s the landscape changed however.

During the 1970s and the first half of the 1980s NC continued to operate as a partnership owned by three different firms. In relation to their owners NC developed a high degree of independence. In 1986 NC was transformed into a company in its own right, listed on the Oslo stock exchange. Aker – with Kværner one of the two major Norwegian players in offshore engineering – first bought Høyer Ellefsen's and, in 1987, Selmer's shares in NC (Steen 1993: 37). This turned independent NC into an Aker company. This also shifted the financial risks for these huge projects from the original owner firms – who never would have been able to survive the financial consequences of the loss of a Condeep-platform – to Aker. At top-level managers from Aker companies, shaped by Bergen's business school tradition, replaced an audacious and entrepreneurial styled leadership dominated by engineers.

In December 1985 and early 1986 oil prices in the international market dropped sharply – from an average of 27,5 to 14,8 US dollars a barrel (Austvik 1989: 19) -, reducing overall profit margins and creating serious cash flow problems for oil companies. Experiences from the 1970s learned that the North Sea was much more expensive to build in than originally expected. The overall level of field development costs had been under discussion for several years, but the 1986 drop of oil prices made the matter much more urgent. This resulted in an industry wide initiative to reduce field development costs through standardization: the NORSOK-project (NORSOK 1995). This renewed cost awareness permeated the whole field.

Simultaneously, NC's competition grew stronger. In 1988 Peconor – a consortium of Norwegian and foreign construction firms established in 1983 – broke NC's 1980s concrete monopoly by winning Phillips Petroleum's contract for a protective concrete wall around the Ekofisk-tank (BT Olje 1988: 4-5). Peconor announced that they would compete with NC for the upcoming contracts on Troll, Draugen and Heidrun.[13]

3.3. Adaptive performance systems

In this overview of NC's history I have been describing Norwegian Contractors as a single adaptive unity. Drawing on evolutionary biologists like Wright and Jacob, Kauffman (1993: 33) conceives of adaptation as a local search process in a space of possibilities, the fitness landscape. But not every change – incremental or radical – does improve the system's *fitness*, that is, its ability to perform its task. The metaphorical image is 'one of local hill climbing via fitter mutants toward some local or global optimum' (Kauffman 1993: 33). Considering the centrality of task performance in this study I prefer Holland's (1995) term *performance system* over the more general term

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[13] Peconor = Petroleum Construction Norway. Peconor lost the battle for Troll, Draugen and Heidrun, all of these contracts going to Norwegian Contractors. Another consortium, SeaCoNor (=Sea Construction Norway), established in 1983, consisting of A/S Jernbetong, C.G. Doris and Skanska, tried to compete with NC, but failed. Peconor was dismantled and SeaCoNor withdrew from the offshore market.

of complex adaptive system. I will write about *adaptive performance systems*.

3.3.1. Performative closure

At this level of aggregation and description the performance criteria that would define NC's fitness would be in economic terms: its ability to sustain a regular cash flow and profitability. In the North Sea area NC had a first mover advantage, but each new contract had to be won under serious competition. Their ability to win new contracts was – at least to some extend – based on NC's demonstrated ability to 'deliver on time and on site'. I will call this their ability to achieve *performative closure*, both with regard to the company's economic performance and with regard to project completion.

Writing about the origin of life Kauffman (1993: 301 ff.) speaks of catalytic *closure* in self-organizing sets or networks of catalytic chemical reactions (autocatalytic sets). It is the whole set of reactions that constitutes an adaptive performance system. Survival in its environment does not depend on (selection against) individual mutations in one of the reaction chemicals but on the adequacy of task performance of the system as a whole (see also section 3.5. and Solé and Goodwin (2000: 227)). In constructivist science and technology studies the notion of closure is used to refer the reduction of interpretative flexibility characterizing the end of a scientific controversy, or the selection of one technical design over the alternatives (Bijker et al. 1987: Bijker 1994). In his works on discourse coalitions Hajer (1995: 22) writes about discursive closure, referring to the process through which a set of diverse claims and discursive fragments, nearly all of them being contested, 'somehow' become related to one another and result in a particular definition of the policy problem. Although used in very different disciplines the notion of closure generally refers to the emergence of some kind of order (socio-cognitive, technical, biological) in interactive (cooperative and competitive) and interdependent processes operating in a selective environment.

3.3.2. Highly connected clusters

Moving down one level of description we can see that Norwegian Contractors was not a single, homogeneous unity, but that is was a heterogeneous aggregate of multiple adaptive performance systems. Stripping the company from all its specifics and adopting Barabási's network vocabulary we could say that NC had a modular organization, in the sense that groups put together to solve or perform specific tasks form highly connected clusters or modules. Each module is connected to other modules with only a few links. Modular organization allows complex adaptive systems to handle multitasking (Barabási 2002: 231-2). In many organizations this takes the shape of departmentalization. NC had a matrix organization: specialized groups, i.e. for design, engineering, marine operations, constituted the permanent and basic structure of the company. For each project, these groups handled the work involved in the protracted pre-contract period. Towards the actual signing of the contract and depending on its terms, (temporary) project teams or organizations were put together for the execution of the contract, drawing on resources from its own base organization and hiring consultants and subcontractors for specific tasks. Consultants and subcontractors were recruited from a network of engineers and engineering companies that was also highly connected: many people knowing each other personally, having worked together on previous Condeep or other projects. A design team like the one that was assembled to design Sleipner A, conceived as an adaptive performance system, straddled formal company boundaries.

In the case of Norwegian Contractors it is also important to distinguish between two sites: the offices at Stabekk, near Oslo's former airport Fornebu, where the design, engineering and accounting were performed, and the construction sites at Hinna in Stavanger and in Åndalsnes, both located on Norway's west coast.

3.4. Culture

Specifics do matter. In addition to a characterization of NC's organizational structure in terms of modules or matrixes, the aggregate of adaptive performance systems can be characterized in social and cultural terms.

Following work in social theory on space, work that is focusing on how people through the way in which they conceive and perceive the world, and through their practices, produce ‘social spaces’, we could speak in Shields (1997) words about *social spatialization*. Societies, but also companies like Norwegian Contractors are socially spatialized. The notion of social space and social spatialization accounts for important cultural, cognitive and practical dimensions of the way in which people attribute cultural and social significance to the world. Social spaces are not a given, they are produced and reproduced; that is, they are emergent, they are contested and they interfere with each other. This interference between social spaces can be negative or positive. Shields (1997) speaks of stress and resistance to refer to the negative frictions in the encounter between different social spaces. I will speak of resonance to refer to positive, enhancing interactions.

In work on organizational cultures there is a similar move towards more differentiated and fragmented perspectives on culture in organizations (Frost et al. 1991). In her history on oil worker cultures in the North Sea offshore industry, Smith-Solbakken (1997: 6), moves from a general notion of organizational culture to a, for her purposes, more appropriate notion of workplace culture. The offshore workplaces that she studied occupied workers from many different organizations, from oil companies but also from subcontractors, but also from different nationalities. These workplaces were places were people from different, similar or opposite, cultural backgrounds encountered each other, adapted and transformed (Smith-Solbakken 1997: 11). Culture is both something that people bring with them, a resource, and an emergent outcome of local interactions that then again can act as a resource.

In empirical, sociological and anthropological studies of scientific practice there is a strong emphasis on the situatedness of knowledge and skills. For Pickering (1992: 3), culture ‘denotes the field of resources that scientists draw upon in their work’. Practice ‘refers to the acts of making … that they perform in that field’. The products or outcomes of practices, Pickering argues, ‘might well function as a resource for future practice' (Pickering 1992: 3). The field of resources that Pickering refers to as culture is heterogeneous, that is, it comprises also, or perhaps primarily, material resources: 'the hammer, nails and planks of wood' to construct a dog kennel.

Hence, adaptive performance systems can be localized in space and time. The performance of the assigned tasks takes place in specific workplaces, the boundaries of which are not defined by the walls of an office or building, but are constituted by the highly connected cluster or network that performs the task. Adaptive performance systems can be characterized by the skills and knowledge that they draw upon to perform their task and by the tools that they use. In and through the performance of their tasks adaptive performance systems gain experience, develop new tools, new knowledge and from their interactions emerge criteria to evaluate the work performed. In these specifics adaptive performance systems can be quite different. The design team of Sleipner A used advanced software packages and mainframe computers to calculate the forces and stresses in cylinders, domes and shafts of concrete under a variety of load conditions. On NC's construction site at Hinna workers use their skills and knowledge to assemble the dense web of reinforcement steel and mix and pour high quality concrete in a continuous process of slip forming. This again is quite different from the accounting department monitoring the economic performance of the project. The understanding of Sleipner A that these different adaptive performance systems achieve is radically different, yet they all must achieve *performative closure* for the specific task that has been assigned to them.

The project, Sleipner A in this case, is not produced by a single adaptive performance system: it moves through several of them. It is transferred from one to another. This transfer can be fixed in terms of specific deliverables that travel from one to the other: a report outlining the basic design of the platform, data batches representing the output of the global analysis (design) and being send to engineering, drawings and material lists traveling to the construction site, the physical structure in concrete and reinforcement steel ready for deck-mating.

In its temporal dimension this movement through multiple adaptive performance systems is directed. Between adaptive performance systems the process is not recursive; there is no going back. As it goes from one workplace, to use Smith-Solbakken's word, to the other it gains in irreversibility (lock-in). The costs of going back and redo earlier work is to high and would take to much time; and time is, given the predetermined start of production, also a cost. On an energy landscape going back would amount to going up the energy gradient again, whereas the movement is downhill to a cost-effective valley floor. On a fitness landscape going back and redo work from earlier stages would amount to stepping down to the valley again and start looking for a new and better way uphill, perhaps on another fitness hill. We will only see recursive movements *within* adaptive performance systems; not descents to the valley floor, but one or to steps down the slope. Of course, the loss of the Sleipner A gravity base structure forced NC and Statoil to go back to previous stages of work.

3.5. Selection

The approach developed here embodies an evolutionary perspective. Hence, selection culls the less fit from the fitter variants. Kauffman (1993; 1995) does not tire to say, that selection does not act on individual mutations but on complex wholes. Within these complex wholes individual variations may be neutral in terms of their effect on overall fitness. And, if several solutions to specific design problems are equally good in terms of overall fitness, why not choose the one that is most convenient, requires less materials or time, or is less expensive. In other words, why not choose (select) the solutions that allow the system, either in terms of work in the process or in terms of costs of the final product, to occupy a lower energy position on the energy landscape. Hence, in terms of fitness, there are environments or regions that are *selectively neutral*: there is a *selectively neutral fitness shell* (Kauffman 1993: 108). Hence, features that are selected because they are equally fit to alternatives and are either equal or lower in terms of energy will be *retained*. They will be incorporated in the (intermediary) products that represent the achievement of performative closure (the whole) and follow along with it to the next stage of work.

Selection is not some mystical force. Selection in the case of Condeep-design is very concrete. In he following chapters I will distinguish three selection levels: a) the credit assignment and reward mechanisms within the design team, b) the design and engineering revisions and verifications that are part of the formal quality assessment procedures involving company internal but also external experts and consultancy firms, and c) the physical environment of the water in Gandsfjorden.

3.6. Comparative note on complexity, interactivity and adaptivity

Before we proceed, a comparative note on the use of terms complexity, interactivity and adaptivity is in order here.

The way in which the terms complexity and interactivity are used here is quite different from the way in which Perrow combines them in his notion of complex interactions (vs linear interactions). For Perrow (1984/1999: 78), ‘complex interactions are those of unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible’. In Perrow’s work complex (and linear) interactions constitute, together with tight (and loose) coupling, a conceptual framework for thinking about accident causation. They are (static) properties that make industrial systems more prone to systemic failure (normal accidents). Complexity theorists look at the density and pattern of interactions as a source of emerging order. The ways in which the emergence of order, of optimal performance, relates to systemic failures is subtler. This is not to deny that this narrative of the Sleipner A GBS loss could be recast in a ‘normal accidents’ framework. In fact, this study contains a telling example of a Perrowian complex interaction.

Rasmussen (1994: 22-3) presented a model of adaptive work performance that comes very close to the framework presented here. With the characteristic emphasis of a psychologist and human factor analyst on human behavior at the ‘sharp end’ of the human/system interface, Rasmussen argued that human behavior in any system is shaped by objectives and constraints that must be respected by the actors for the work performance to be successful. Such objectives and constraints define the boundary conditions of a workspace, a design envelope, within which the human actors can navigate freely. According to Rasmussen, the choice among several possible work strategies for navigation within the envelope specified by these boundaries depends on subjective criteria, related to process features such as time spent, work load, pleasure, excitement of exploring new territory. Work practices will be characterized by local, situation-induced variations within the workspace. Rasmussen argued, that the result will very likely be a systematic migration toward the boundary of acceptable performance and, when crossing an irreversible boundary, a local work accident may occur. Emphasizing the local interactive and self-organizing processes underlying this drift-like migration, he draws an analogy with the 'physics of interactions' that produce the Brownian movements of molecules of a gas. The metaphor of Brownian movements might suggest an image of erratic and undirected drift within a space of possible work strategies. According to Rasmussen there is some direction, though. Although he does not elaborate on it, Rasmussen introduces the notion of a *gradient* to indicate some directionality in local adaptations.

> *Such variability will give ample opportunity for the actors themselves to identify 'an effort gradient' and management tends to always make a 'cost gradient' very visible to the staff (Rasmussen 1994: 23).*

Rasmussen does not use the metaphor of a fitness hill, but it is not difficult to conceive of his workspace as Kauffman's selectively neutral fitness shell hovering around the top of such a hill, a region in which adaptive changes will be considered neutral, or valued positively (because of their lower energy state), without them affecting the overall task performance of the system. It is important, however, to recognize that the location of the boundaries of the envelope can only be reconstructed with hindsight, in a secondary process of accident investigation.

Chapter 4

Sleipner A: adaptive changes before contract

We are now prepared to examine in detail the design and engineering process of Sleipner A. An analysis along the conceptual lines set forth in the preceding chapter can be pursued at various levels of description and aggregation, requiring different research methods though; it may even move between levels. The following chapters will focus on NC's design team, led by NC personnel but also comprising personnel from other engineering firms. From the previous chapters we should recall that the circumstances in which the design team was assembled and had to work were the result of an adaptive search process performed by Norwegian Contractors as a company. Starting out in the 1970s as a partnership of entrepreneurial firms with core competencies in project management and concrete constructions, NC consciously invested in the development of in-house competencies in global analysis and design, in mechanical engineering, in marine operation – in order to be able to offer turn-key solutions. A dramatic 1986-drop in oil prices and profit margins, inducing an industry wide awareness of overall field development costs[14] (Austvik 1989: 19), constituted an important change in NC's environment (and fitness landscape). So did the emergence of serious competition, with Peconor winning the contract for the Ekofisk wall in 1988, breaking NC's concrete monopoly for the first time. Peconor announced that they would compete with NC for the upcoming contracts on Troll, Draugen and Heidrun (BT Olje 1988: 4-5).

4.1. Instable fitness landscape

Condeeps – as any offshore field development solution – had long lead times. The licenses for the Sleipner-field were allocated in 1976.

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[14] This resulted in an industry wide initiative to reduce field development costs through standardization: the NORSOK-project (NORSOK 1995).

Owning 49,6 % of the license for the Sleipner field[15], Statoil was assigned as operator on the license, being responsible for negotiations with customers for the gas to be produced, for the fabrication and installation of production installations and for operations on the field. Development of the field was delayed due to the rejection by the British government of a contract negotiated by the British Gas Corporation (Selvaag 1988). The contract was about to be signed; for this specific task performative closure had been almost achieved. The British government's rejection of the contract threw Statoil back into the valley and forced them to look for a new fitness hill. Sales contracts had to be renegotiated, having consequences for the general technical infrastructure of the field. Instead of landing the gas on the British shore it now had to be transported to Belgium and Germany. This second time around, performative closure was achieved. Conclusion of these major sales contracts set a time- and deadline for the commencement of production and delivery of pre-arranged quantities of gas.

Simultaneously the operator had to evaluate various technical field development solutions for feasibility and profitability (Gudmestad et al. 1993: 9 ff.). Fixed or floating? Steel or concrete? A formal plan for development and operation of the field had to be submitted to the Norwegian authorities for approval by parliament. Sleipner A was going to be the first production platform on the field: a fixed solution in concrete. These early decisions started Statoil on a uphill trajectory that would become increasingly irreversible. This trajectory was not predetermined, however. It would have to be explored in an adaptive search process. Neither was it clear where the top of the hill would be.

The shape of fitness landscapes, for any adaptive performance system, is influenced by the activity of other actors. In the mid-1980s the landscape became very unstable.

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[15] This is including 29.6% for SDØE, the Norwegian state's direct financial interest (SDFI). The remainder of the license was owned by: ESSO Norge a.s. 30.4%, Norsk Hydro Produksjon A/S 10.0%, Elf Aquitaine Norge A/S 9.0%, Total Norge A/S 1.0%.

As Norway established itself as a major supplier of gas and oil, the state wanted, in Gro Harlem Brundtland's (1989: 19) words,

> *to secure maximum economic and social benefits from our energy resources. This requires that specific goals relating to the energy sector be attuned to overall economic needs of the country, to regional policies and to local as well as global environmental needs. … in a long term perspective.*

To secure a larger income from offshore activities the Norwegian state had, in 1984, taken a direct financial interest in oil and gas production in the North Sea. Through this direct financial interest the state directly owned part of the license on a field, contributing in the investments but also taking their share in the profits generated – in addition to taxing the profits of other oil companies owning shares of the license. 29.9 % of Statoil's 49.9 % share in the Sleipner license were transferred to the states direct financial interest; effectively transferring a substantial part of the revenues from the Sleipner field out of the company. The oil prices had peaked in the first half of the decade but dropped sharply in December 1985 and early 1986, further deteriorating future cash flow prospects for the exploitation of the Sleipner-field. The drop in oil prices induced a high awareness of the necessity to contain overall field development costs. This resulted in an industry wide cooperative initiative to reduce field development costs through standardization: the NORSOK-project (NORSOK 1995).

Norwegian Contractors had successfully risen to the challenge of (and achieving performative closure in) building the gravity base structures for Gullfaks A, B and – hitherto the largest ever – Gullfaks C: production platforms for the first Norwegian oil field developed and operated by Norwegian companies only (Nordås 2000). However, a fatal accident in 1985 revealed that NC was not invincible either. On November 4, 1985, CONCEM, a barge moored in Gandsfjorden to the side of Gullfaks B for the mixing of concrete, capsized and was lost, killing 10 out of 22 people on board (Laake et al. 1985).

4.2. The Concept Report

Having concluded sales contracts for gas from the Sleipner-field with large customers, the next step in the process for the operator, Statoil, was to develop a basis for the contracts with engineering firms for the fabrication of the platform.

As a basis for the contract between Statoil and NC for the fabrication of Sleipner A, in 1987-’88 they developed – through collaborative work - a Concept Report. Gudmestad et al (1993:15) conceived of this process – that could take up to a year – as an iterative, but basically linear process. The Concept Report translated physical characteristics of the site (water depth, seafloor conditions), estimated weight of topside installations, required storage facilities, etc. into a basic design for the platform: number, diameter and height of the cells in the base; number, distance, heights and functions of the shafts. Taking into account applicable regulations issued by the Norwegian Petroleum Directorate and cost estimates, the Concept Report set the boundaries for a feasible, reliable and cost-effective platform. In terms of the fitness landscape metaphor, the Concept Report staked out the perimeter of a region around the top of a hill, representing a performance optimum. From here on it is, as Steinar Leivestad at the Norwegian Construction Standardisation Board puts it, ‘a matter of designing according to assumptions’. Stay within the boundaries (of the envelop).

4.3. The Statfjord A problem and a hole in the tricell top dome

In its details the Sleipner A Concept Report was not based only on field data and functional requirements. Solutions to problems experienced in previous Condeep-platforms carried over into the design of Sleipner A. According to Per Irgens, NC’s SLA project manager, NC ran into serious problems in every Condeep platform built, but they had always been able to solve these problems. While building the Statfjord A platform in Gandsfjorden in the 1970s, NC encountered a serious problem with crack formation and propagation in the tricell corners. The hydrostatic pressure of the water column in the tricell pressed the Y-shaped tricell corner apart where there was no ballast water in the cell to counteract this pressure. The problem emphasized the tricell corners as particularly vulnerable and critical areas in Condeep design. In subsequent projects the ‘Statfjord A problem’ was solved through changes in the geometry of the tricells and the placement of bicycle handlebar shaped reinforcement bars across the corner, stopping the propagation of any cracks that might appear.

In all projects prior to Sleipner A water pressure in the tricells was an issue. Constructing the Gullfaks platforms for deeper water the tricells were designed with a closed top dome, fitted with a piping system for letting in or pumping water out of the tricells as part of the ballasting and balancing operations. As a result, during construction and installation NC had *control* over the water pressure in the tricells and could *reduce* the pressure if required. This closed dome arrangement served as a protection mechanism for the tricell corners and it would, in case of crack formation, prevent the pressure of the full water column in the crack and thus reduce its propagation.

Sleipner A was designed with an open hole – with a diameter of 50 cm – in the top dome of the tricells. The mechanical installation required for the in- and outlet of water was deemed not to be necessary in this case. The Statfjord A problem had been solved through changes in the geometry and reinforcements and proved to work well in the Gullfaks series. The maximum hydrostatic pressure on various levels of the tricell corners during the various phases of construction, deck mating and installation could be calculated exactly and incorporated in the Concept Report as boundary load conditions.

Of course, given the number of tricells in a Condeep (32 in Sleipner A) this change in the design resulted in a reduction of costs. I have not been able to establish the primary motives for the open hole in the top domes of the tricells.[16] However, there is no reason to

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[16] The engineers I interviewed were involved in the post-contract design and engineering work. As soon as I became aware of the difference between Sleipner A and previous Condeeps, I raised the issue of the hole with them all. Several of them had no recollection of the hole at all, and none could provide the primary reason for the hole. Some provided suggestions of the secondary uses to which the hole could be put. Tormod Dyken entertained a train of thought

suspect that it was motivated by ‘cost reduction at the expense of technical reliability’, that is to adopt design features that were judged to be unsound by the engineers involved. When, from an engineering perspective, a top dome with a hole and a top dome with pipes and valves were considered to be equal, this feature was in a selectively neutral fitness shell. When equal in technical fitness the variant that would produce a lower energy/cost level constituted the preferable alternative, also for the engineers. Why have a mechanical installation of pipes, pumps and valves if you do not need it? The increased cost awareness in both Statoil and the new management of – the now Aker owned - Norwegian Contractors constituted a selection environment that would positively value cost reducing design changes that were judged to be technically sound by Statoil’s Sleipner A project group and NC’s engineers involved in the interactive process of elaborating the Concept Report. In other words, the design change resonated or correlated, as Marion (18, 74) calls it, with the field development cost awareness that permeated the industry. Resonance or correlation is the interactive mechanism through which the behaviors of different actors achieve a measure of sync-ness. The tricell top dome with open hole was selected and it was retained in the directed movement of the project through the next stages where different adaptive performance systems execute their specific tasks.[17]

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assuming that you would have a hole when you wanted full water pressure on the inner walls of the tricells to reverse the pressure difference across the wall, to prevent hydrocarbons seeping out into the water in the tricell that would eventually end up in the sea. Perhaps in relation with new environmental regulations. However, I have not been able to confirm such a change of regulations. As motives do not explain the overall behaviour of systems, the consequences of the hole are more important than its reasons.

[17] How should we call a design feature like this? In hindsight we can see that the hole, in interaction with the crack and the leak, was one of the elements constituting a Perrowian complex interaction resulting in the actual loss of the platform. Should we call it a mistake, an error, a lapse of judgement? Or perhaps, in Reason’s (1993) words, a latent failure. The problem is that most of the time, latent failures can only be recognized after the accident and through secondary accident investigation processes. In the primary process there is no error.

The open hole was small at first. Later in the process it was enlarged to a diameter of 50 cm. The enlargement would not make a difference in terms of water pressures, but it would allow secondary uses of the hole, i.e. the insertion, if necessary at some point in the lifetime of the platform, of submersible pumps.

4.4. Quality Assurance according to standard

In previous Condeep projects Statoil's respective project groups spent a substantial amount of time on design reviews. Induced by the renewed, industry wide cost awareness Statoil wanted to cut back on the number of hours spent on quality assurance work by its own personnel. In the Sleipner A project Statoil put emphasis on the contractor's own responsibility for setting up and complying to in-house quality assurance procedures.

Statoil-SLA was quite explicit about the QA requirements that were to be incorporated into the contract. Parallel to the elaboration of the Concept Report NC developed a Quality Assurance Manual in accordance with national (NS 5801) standards, 'adjusted to meet Statoil's needs related to critical contracts' (Jersin & Søreide 1997: 16). The manual was not a description of the working practices that NC had evolved over the years in which it had successfully built eleven Condeep platforms. It was developed on the basis of formal standards, and in accordance with 'practice in the trade', but the standard was not 'particularly well suited for engineering tasks of this type' (Jersin & Søreide 1997: 14).

There was a substantial gap between an entrepreneurial practice that had proven itself to be successful and Statoil's emphasis on compliance with the formal protocol of national and international standards. The encounter between two different cultures, associated with two different workplaces and adaptive performance systems that were irreversibly bound to cooperate, created serious friction and stress. Statoil representatives pushed NC's engineers in this matter to the brink of a conflict that, according to Per Irgens, had to be resolved at top managerial level.

In compliance with NPD regulations saying that an independent, third party engineering consultant should be involved in the quality assurance procedures, Statoil negotiated a contract with DNV-company Veritec. The terms of the contract were limited though, in the sense that Veritec was not to do a complete verification of all documentation produced by NC in the course the design work, but that Statoil-SLA would select documentation to be reviewed by Veritec from the 'deliverables' that Statoil received from NC. For each of these selections Statoil would issue a specific work order.

Statoil audited NC's QA procedures, had them make some more changes having to do with differences in the interpretation of formal regulations and rules, and found them, in the end, to be satisfactory. Between the two an EPC-contract was signed on June 30, 1988, comprising the engineering (E), procurement of materials (P) and construction (C) of Sleipner A, including marine operations[18] (Statoil 1991: 12).

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[18] The contract for the main mechanical outfitting in the GBS went to Rosenborg Verft. Aker Engineering designed and built the topside structure (steel decks and gas processing installations).

Chapter 5
Sleipner A: Global Analysis (GA)

Global analysis is the procedure for calculating the forces and stresses that occur in the concrete cylinders, domes and shafts of the platform under a large number of different load situations that can occur during the various phases of fabrication, transportation, installation and use of the platform. With regard to load situations, think of high waves and undercurrents in the sea and raging storms above water level, but also of falling objects (tools) or ships colliding with the platform. The platform must be able to resist all these different load situations and even be able to sustain considerable damage without loosing its technical integrity. The mathematical equations describing the continuous forces and stresses in curved shapes of concrete are difficult to solve. For practical design purposes an approximation technique has been introduced that represents curved and continuous shapes as being composed of discrete and finite elements (rectangles, triangles, etc.): finite element analysis. Forces are calculated in the corners of these finite elements, followed by interpolation between them. For a large structure like a Condeep-platform even this technique requires a considerable amount of computer time and thus, costs. Developing or modeling the mesh of finite elements representing the platform and its various design features is an important part of the design work, in addition to defining load situations and entering the data representing them into the calculations.

5.1. GA in-house

Norwegian Contractors decided to take responsibility for the GA for Sleipner A. This is significant, because it was the first Condeep for which NC would stand for the analysis. As an adaptive change, this decision represents a move on an adjacent opportunity for which NC had prepared itself and that fitted with a conscious strategy and effort sustained over the years, to develop turn key capability. NC had invested in its in-house GA competence and in software development

(PATPRE) for automation of load data inputs (see section 3.2.3). Now, with Sleipner A, the opportunity arose to include the global analysis in the offer to Statoil as work performed by and under the responsibility of Norwegian Contractors, instead of contracting it out.

In the spring of 1988 Einar Fjøsne produced time budget estimates for the global analysis. NC also got an offer for the GA from Norwegian Offshore Contractors (NOC), forwarded and signed for by Dr. Tech. Olav Olsen. Time budget numbers put to this offer amounted to the double of NC's in-house estimates.

Furthermore, Veritec, the DNV-company that had done the GA on previous Condeep-projects using a software package called SESAM-69, was shifting to a newer version SESAM-80. Veritec had already ceased to maintain SESAM-69 while designing Gullfaks C. Already in that project NC itself had taken responsibility for the maintenance work on SESAM-69. NC's engineers who had experience with SESAM-69, considered the new version SESAM-80 less well developed and tested. They expected SESAM-80 to generate more unexpected problems than the NASTRAN-package that they themselves had used in ten large studies. Hence, in terms of quality assurance – which Statoil wanted NC to take responsibility for – an NC led GA using NASTRAN was the reasonable choice (NC 1995: 4-10). This resonated positively with the fact that the comparison of time budget estimates also spoke in favor of NC doing the job in-house.

Again, when two alternatives are considered to be equal from a technical or engineering perspective, they are in a selectively neutral fitness shell and the one that produces or represents a lower energy/cost level will be selected. When one is favored on engineering grounds, then it would be unreasonable to expect that the less fit and more expensive alternative would be chosen. At a higher level of description and aggregation, that is, for the company as a whole, doing the GA in house would amount to a next step in climbing the Condeep-fitness hill. At the level of description of the design team, it would be a challenge to do the GA on Sleipner A in-house and see the platform actually being built; after years of involvement in 'studies', in handling Computas' and Veritec's GA-output, in QA work and in software development. It was a challenge and responsibility that they would not take lightly. They were anxious to demonstrate that NC's strategic investments in GA competence would bear fruit.

5.2 Staffing the adaptive performance system (design team)

Choosing NASTRAN as the GA-software package to be used for Sleipner A, effectively excluded involvement of Veritec in the actual design work. This implied that NC, for the staffing of the design team, would have to draw on its own personnel and on consultants from the group of engineering firms in the immediate vicinity of Norwegian Contractors. These were people that knew each other well through collaboration on previous projects. In addition to its own personnel NC hired consultants from Norwegian Offshore Contractors, but also from Dr. Tech. Olav Olsen, the engineering firm that would do the engineering.

The sum of the design work was broken down into various subsets (modeling of element mesh, running of the program, response control, quality assurance) for which the various members of the team were responsible. The hired consultants could engage personnel from their home company in the execution of the work.

Given the central position that Norwegian Contractors had achieved over the past 15 years, this set of people and companies represented one of the top expert environments in offshore constructions in concrete in Norway. Located close together in the Oslo region, they were not only geographically close together. The number of formal and informal links and interactions among the participants in this group was high. Some of NC's personnel held positions in one of the subcontracting firms, before moving to NC. Some of NC's younger engineers came from the technical university in Trondheim, the interactions with that environment were less frequent and intense though. As an adaptive performance system, with the specific task of detailing the design of Sleipner A, the design team was nested within NC's project organization for Sleipner A, straddling, however, company boundaries.

5.3. Approximation, judgment and uncertainty in the finite element method (FEM)

For the purpose of solving practical structural engineering problems, in the mid-1950s, a method was introduced that modeled continuous structures as if they were composed of discrete, finite, elements or building blocks with regular, geometrical shapes: the finite element method (FEM)(Clough 1979). These elements were represented by a limited number of points, i.e. the corners of a cube. Tensions and stresses were calculated for each of these points and interpolated to positions in between. Still, for large structures like Condeep-platforms, the amount of calculations to be performed was enormous. It was recognized that the FEM-version was an approximation to the continuous real thing. However, supported by elaborate testing of results against full-scale tests and numerical calculations using other equations and software packages, the method made the job doable. The use of the finite element method was well established in the offshore industry, both for steel and concrete structures. It had been used for all Condeep-platforms. It was taught at the technical university in Trondheim and it was approved in national construction standards and NPD regulations concerning offshore load bearing structures. The industry wide trust in the accuracy of the results that could be obtained using the finite element method was reflected in the (conditional) allowance of the use of reduced safety coefficients if the most unfavorable tolerance limits are taken into account (Petkovic 1997).

However, the use of the finite element method was never a plug-and-play solution. It was not a (deterministic) rule-based procedure. Some degree of unpredictability and uncertainty was still inherent in the software. The design of the overall element model, covering a quarter of the whole (biaxial symmetrical) platform, as well as the smaller models for recurring elements like tricells – which were called super elements, required experience based engineering judgments. Judgments had to be made about the number, size and type of elements, and about the *allowable degree of irregularity* (deviation from perfect geometrical shapes)[19] necessary to make the elements and super elements fit together in curved shapes and joints.

Choices made in the FEM had also economic consequences. An element represented by 8 points required fewer calculations and computer time than 20 point elements. A balance had to be struck between the required accuracy of the results, technology at hand, hours of labor and costs (Ramstad 1979: 8.1). It was not the case that the smaller the size of the elements, the greater the number of elements and the more points in an element would give the better solution. There was no absolute ban on the use of skewed elements, although it was known that some shapes – for example very long elements – could produce inaccurate results.

The behavior of the elements in the GA and in the post processing of the GA output in the engineering phase was characterized by an optimum. The location of that optimum however, was not a matter of mathematical certitude, but of experience based engineering judgment.

5.4. Slimming as engineering optimization

With the advanced design tool of NASTRAN at hand the design team for Sleipner A started on an adaptive search for an optimal fulfillment of their task: the detailing of the design of a Condeep platform that was simultaneously reliable, functional and cost-effective. This was very much an optimization process, that is, optimization from an engineering point of view. According to Tormod Dyken, one of the senior engineers in NC, NC’s management did not put pressure on the design team in order to cut corners.

Engineering optimization was something that the engineers involved toke pride in from a professional point of view. Given the accuracy of the design tool, why should you have thicker walls than needed? Why would you have reinforcement steel where it was not required? Reducing the thickness of a wall with 1 cm would result in a

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[19] A rectangular element would be irregular to the degree that angles deviate from 90º.

reduction of the amount of concrete necessary for construction that alone would already be enormous.

There was a lower limit though. Workers on the construction site required enough space to find room for all the reinforcement steel. And a minimum thickness of concrete covering the steel bars was required to prevent erosion of the steel by penetrating salts from the seawater. However, compared to the Gullfaks platforms, that were built under the favorable circumstances of high oil prices and high profit margins, there was much to be gained by *slimming* Sleipner. The total volume of water displaced by the GBS would still be the same. Slimming would reduce the total weight of the concrete structure though, adding to the difference between upward pressure and total weight that determines the maneuvering space for loading and marine operations. And it would still be in compliance with NPD regulations allowing the use of reduced safety margins.

5.5. Smart solutions

The bearing capacity of a thinner wall depended also on the length of the wall. At some point in the optimization process it was discovered that, given its thickness, the length of the tricell walls was to long. The solution to this problem that was proposed was to go back to the model of the element mesh and add a triangular element in the sharp tricell corner. The alternative, making the walls thicker again, would increase the weight of the GBS and the total amount of concrete again. The triangular element filling in the tricell corners solved the problem by reducing the length of the tricell walls between its supports. The amount of concrete necessary to fill in the corners on the construction site was limited.

Again there is a choice between two alternatives, but this time they were not considered to be equal. According to Tormod Dyken, one of NC’s senior and experienced engineers, this was considered to be a *smart* solution. Within the immediate environment of the team this solution was *rewarded*, it was positively *selected* as being a good and smart thing to do.

The resulting reduction of the number of elements in the tricell wall from six to four was considered not to be of any consequence for the accuracy of the global analysis[20]. It was considered to be neutral. Furthermore, this solution held its ground in the higher-level internal engineering meetings and design review meetings in NC. Neither was it selected against in the verifications performed by Veritec or Statoil's SLA-group.

5.6. Increased topside weight

Statoil awarded the contract for Sleipner A's topside to Aker Engineering. In August 1988, after the signing on the contract on June 30 and after the completion by NC of the element model, Statoil announced that the topside would be heavier than estimated in the Concept Report. Statoil forced the design team to go back and redo part of the work that had already been performed.

The increase was larger than the difference between the upward pressure produced by displaced water and the total weight of the structure. It also consumed the maneuvering space that the slimming had added. Increasing the total volume of the GBS, and hence, the volume of displaced water, could solve the problem. The only feasible way to do that, without affecting the geometrical relationships between the shafts and the decks, was by increasing the height of the cylindrical cells. NC calculated the additional costs for this post-contract change. Arne Bjørlo, NC's engineering manager for the Sleipner A project, recalls the unwillingness of Statoil to pay that price and negotiations for cheaper solutions. Eventually, the height of the cell walls was increased with 1 meter[21] (NC 1995: 7-8).

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[20] In hindsight it is possible to identify this reduction of the number of elements in the (model of the) wall as an important factor contributing to the underestimation of shear forces in the GA. But was there a mistake or error in the primary process?

[21] I have not been able to establish whether this 1 meter increase of the cylinders' height restored the 'manoeuvring margins' to previous levels or whether this 1 meter was 'just enough'. In the latter case, any proposal that would increase the weight would find itself in a negative selection environment.

5.7. Skewed elements

Not every proposal put in writing by the design team was applauded. Notes from internal meetings reflect proposals that were rejected, either on technical grounds or on grounds of additional costs or work that they would entail. The environment in Norwegian Contractors was selective.

In October 1988 Dr. tech. Olav Olsen put the degree to which irregular or skewed elements were used in the element model (in the top domes of the cells and in the tricells) on the agenda. The skewed elements would entail two weeks of extra work in the preparation of the post-processing of the GA results in the engineering phase (NC 1995: 7).

Verification reports from Veritec expressed concern about the consequences of irregular (long and narrow) elements for the accuracy of the GA results (NC 1995: 18). The design team responded to these concerns by initiating special verification activities performed by Grosch and Brekke, consultants from Norwegian Offshore Contractors, responsible for verification and response control.

Again, the finite element method was not a rule based, deterministic activity. There was no general and absolute ban on the use of irregular elements, violation of which would have constituted a recognizable error. What was the team's frame of reference for judging which irregular elements should be corrected, and to what degree, and where would they be of no consequence? The obvious place to look for a frame of reference is within the team itself: their experiences, the preparatory work performed, the tools they use, the books they had on the book shelf.

NASTRAN itself did not prohibit the irregular elements used in the model, although it had internal functions that would not allow the use of very irregular elements. According to NASTRAN manuals the usability of irregular elements depended on the angle between the sides of the rectangle. H.G. Schaeffer's 1982 *MSC/NASTRAN Primer; Static and Normal Modes Analysis*, *a study on computerized* *technology* (3rd edition), the book that in NC was used as a handbook for users of NASTRAN, concluded that:

> *General good results are obtained for skew angles up to 45 degrees. For larger angles the results deteriorate rapidly' (cited in NC 1995: 19).*

The irregular elements used in the tricell element model had angular deviations of 13 and 26º, hence considerably less than 45º.

Some of the engineers in the design team had experiences from designing steel structures in which similar skewed elements were used. Although steel is not concrete and material matters, the use of skewed elements as such was not new, and concerning the significance of the degree of skewedness in relation to the material (concrete or steel) there was no standard.

The handbooks that some of the younger engineers in the team had used during their training at the technical university of Trondheim, books authored by the leading academic FEM environment in Norway, did address the issue of skewed elements with much emphasis. If there was a shape that was of concern, it was the very long and narrow element, defined not by angles but by the ratio between the sides. These were the elements that Veritec's verification reports referred to.

Perhaps more important, in preparation of his verification activities Brekke reviewed the design and verifications reports of Gullfaks C. Skewed elements similar to the ones used in Sleipner had also been used and approved in the top domes of the cells in Gullfaks C.

Grosch and Brekke reviewed all the instances in which skewed elements were used in the model for Sleipner A. They proposed several instances, i.e. in the top-domes of the cells, in which the degree of irregularity should be reduced. Grosch and Brekke's proposals were discussed in the team against the background of experiences and knowledge of the state of the art they had. The degree of irregularity in the tricells was not considered to be of consequence and thus remained. In other words, with respect to the skewed elements in the tricells this process that explicitly focused on skewed elements was selectively neutral. Neither were they selected against in subsequent checks and verifications performed internally in NC or by Veritec or Statoil. Just like the hole in the top-dome of the tricells,, the slim walls, the filled in tricell corner, also these skewed elements in the tricell walls were retained throughout the directed movement of the project through the various adaptive performance systems and workplaces.

NC’s design team completed the global analysis two months behind schedule. The rationalization of loading data input with PATPRE didn’t pay off. Repair work on the program and manual data input delayed the design process, in addition to the delays caused by the extra work generated by the post-contract increase of the weight of the topside and the corrective work associated with skewed elements. Although too late, they achieved performative closure for their part of the job. The project could now be transferred to the next adaptive performance system for the engineering of the platform, work to be performed by Dr. tech. Olav Olsen.

Chapter 6

Sleipner A: Engineering

Engineering is the procedure through which the results of the global analysis are translated into dimensions and placement of reinforcement steel bars, drawings and material lists. To a large degree this procedure is also computerized. Engineering comes ‘after’ the global analysis and the software package used is called POST. As one of the deliverables of the GA the design team produced a printed report that was subjected to final internal and external design revisions and past the test. In the printed report not all results could be visually displayed. Only a selection of typical design details and loading scenarios were displayed visually in graphs. Much of the GA results remained hidden in digital data batches and send over directly to Dr. tech. Olav Olsen (OO) who would do the engineering, using the GA results as input data for their own post-processing software package, POST. The output of POST would indicate where the strength of the concrete alone would be sufficient and where reinforcement steel had to be inserted.

6.1. Rationalizing on drawings and reinforcement

OO had done the engineering for all previous Condeep platforms. Although the firm was the obvious candidate for the work, for every new project a new contract had to be negotiated with NC. Against the background of the renewed cost awareness in the industry, in March 1988, OO offered some suggestions on how they could rationalize the engineering part of the work. Here too some adaptive changes were made. According the Tore Olsen and Kåre Hæreide at OO the company knowingly signed the contract based on the conviction that the quality of the work would not be compromised from an engineering point of view.

One of the suggestions that were incorporated in the contract was a substantial reduction in the number of drawings to be produced. A drawing of a tricell for example would visualize the tricell’s geometry and dimensions in a horizontal plane, including the shape and placement of reinforcement steel *in a maximum situation*, that is: in a situation in which all of the various bars would be present. No separate drawings would be made for situations (i.e. in other vertical levels of the tricell) in which not all of these bars would be present. A list representing vertical levels would indicate the number of bars to be placed per meter. Such a list could contain zero's, indicating that some bars would not be present at some levels. According to Olsen and Hæreide, this was not unusual. In sites where the strength of the concrete was sufficient to resist the expected loads there would be no reinforcement steel. Neither would the absence of reinforcement steel be obvious in the maze of steel on the construction site, where the specific problem and skill of the workers consisted in finding room for all the steel that had to fit in.

Olsen and Hæreide recalled a proposal to place a minimum amount of reinforcement steel at every level, irrespective of the result of the GA and post-processing. After discussion the proposal was rejected. It was selected against; and by now it is easy to understand why. It would require additional steel and incur extra costs. It would add weight to the GBS, and weight had become a critical issue following the post-contract increase of the topside weight. Slimming had reduced the space available in the walls, and finding room for the steel was always a problem on the construction site. And finally, confidence in the accuracy of the results of the GA and post-processing, confidence in the software and computer tools that were used in the design and engineering, supported the judgment that extra bars really were not necessary.

6.2. T-headed bars

A first version of drawings of the tricell produced by OO showed the typical bicycle handlebar shaped reinforcement bar in the tricell corner; that is, the (inherited) solution to the Statfjord A problem (of crack formation in the tricell corner) that carried over in subsequent Condeep designs.

During the engineering process OO received a letter from NC asking whether straight T-headed bars produced by Metalock

Industrier A/S could be used instead. According to Tormod Dyken, who worked for Metalock before moving to NC, these T-headed bars were the result of a continuous process of product development and innovation in the field of high performance concrete construction and reinforcement. They were specifically designed and tested to withstand out-of-plane shear forces in heavily loaded building floors, offshore platforms and bridges. They are easier to place and handle than bend bars and stirrups. NC had used some 80.000 T-headed bars in Gullfaks C (Berner et al. 1991). NC had still an unused batch on stock at NC's construction site in Stavanger. OO checked the usability of these T-headed bars and found them to be appropriate. Again, engineering judgment and economic considerations resonate to positively select a proposed design change that is considered to be an improvement.

The next version of drawings showed the new T-headed bars, placed – like the runs of a ladder – in line in the vertical plane. Neither the use of the bars nor their arrangement was selected against in internal or external design review and verification procedures. There was no reason to object to them. Hence, they were retained; also in subsequent verifications by Veritec, for which Statoil's Sleipner A project group specified the work orders and assigned the budgets. There still was: NO ERROR!

The set or network of people and companies in Oslo involved in the design and engineering of Sleipner A had successfully achieved performative *closure* and passed through all quality checks that it was exposed to. Drawings and lists of materials could now be sent to the construction site at Hinna in Stavanger. The design contained a number of features, changes when compared with previous platforms, through which the design migrated or drifted slightly on its fitness landscape. However, there was no indication that it had drifted towards or outside the boundaries staked out by the Concept Report. The drift produced in the adaptive search for an optimal design remained within what Kauffman (1993) called a *selectively neutral fitness shell*, the boundaries of which were constituted by locally relevant criteria for good work, by local credit and reward processes within the design team and approval in and through the formal internal and external quality assurance procedures.

Chapter 7
Conclusion

7.1. The final selection environment

At NC’s construction site at Hinna in Stavanger Sleipner A was built according to specifications, drawings and material lists received from the engineering offices in Oslo. Tools employed shape the understanding of the construction one is designing and building. For experienced construction workers a Condeep platform consists of the physical shapes and volumes of steel and concrete; not of tensions and stresses and computer generated data and plots. At the construction site no one could have observed something out of the ordinary.

There was NO ERROR there either. Not until the completed concrete structure sprang a leak during the controlled ballast operation in preparation of deck mating. The physical environment of the water in Gandsfjord constituted the final selection environment. The full and uncontrolled force of the water column on the walls of the tricells produced a crack that propagated around the T-shaped ends of the T-headed bars and through the thickness of the wall into a shaft. The formation of the crack probably shifted tensions in the whole circular shaft wall, producing cracks in one or two other adjacent tricell walls.

The holes in the top-domes of the tricells allow for the influx of a continuous flow of water, only constrained by the diameter of the hole. More water surged into the shaft than the ballasting pumps could handle. This is a typical Perrowian complex interaction, defined as ‘those of unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible’ (Perrow 1984/1999: 78). A design change that was considered to be an improvement, or at least neutral and convenient, in the process of elaborating the Concept Report, interacted unexpectedly with the size of the crack. The absence of a controllable device to restrict the influx of water contributed to the loss of the platform. Perhaps with such a device the platform could have been kept afloat. It is impossible, however, to say whether it would have been possible to repair the platform. Sleipner A was evacuated. It capsized and sank, imploding on its way down before hitting the seafloor.

7.2. What are the lessons to be learned?

Alert Gaard, Statoil's engineering manager on the Sleipner A project – received a phone call from the company's site representative at Hinna 'with the unbelievable news that what never could happen had happened' (Gaard 1992: 3). Up to the moment of the loss there had been no error, not in the primary process. To the contrary, Statoil's Sleipner A group, NC and its subcontractor Dr tech Olav Olsen had produced an *optimized* Condeep platform. In the process they adapted successfully to the changes in economic marked conditions and to an unforeseen increase in topside weight.

The errors were reconstructed in secondary processes of post-accident investigations in which investigators knew about the disastrous outcome. In their report reviewing quality assurance procedures Jersin and Søreide (1997: 40) drew explicit conclusions:

> *The identified faults which originated in engineering and verification should in theory have been prevented by the parties' QA systems. Given that the errors were made, the QA systems should have detected the errors and subjected them to non-conformance control and corrective actions, before significant conclusions arose.*

In theory, yes, and given the errors, yes, the QA systems should have detected the errors. But there were no errors. Jersin and Søreide also concluded that,

> *[o]n the whole, the formal QA requirements stated to the parties were in accordance with common practice within the trade at the time. The reason that the errors in calculation and location of reinforcement were not detected in spite of this, was that the QA systems were not adequately implemented and followed up by the parties. … In particular this element [Design Reviews] have obviously not functioned as intended. (Jersin & Søreide 1997: 40 - 1)*

NC was criticized for not following up completely the comments in verification reports concerning the use of skewed elements. They removed some but left others, that turned out to be fundamental errors.

NC should have removed all skewed elements. But, there was no absolute ban on skewed elements and each and every instance required and received experience based engineering judgment. In hindsight, yes, NC has learned something about the behavior of the 8-node elements – and the degree of irregularity – used in the NASTRAN and POST. According to Tormod Dyken, they also learned – after and through the accident – that the optimal number of elements in the tricell wall was six, and that filling inn the corners of the tricells with triangles – the smart solution - effectively reduced the number of elements to four, shifting the GA away from its optimum.

This account of the Sleipner A GBS Loss demonstrates the limitations of approaches emphasizing the eradication and control of errors, or more generally deviations. It also demonstrates the limitations of an accident investigation approach focusing exclusively on deviations from formal rules and regulations, and of a managerial policy focusing exclusively on the management of compliance. In adaptive performance systems there will always be deviations from formal regulations, because the protocol does not describe how practice works. Most of the time, deviations have nothing to do with the causal sequence of events leading to an accident. In practice, it might be hard to determine what constitutes a deviation, when adaptive changes are considered to be neutral, just convenient, or even smart. Or it might be hard to determine (in first order processes) what the rule is. Or as Law points out in a study of the Ladbroke Grove train accident, deviations from formal safety regulations may be necessary to 'repair' the frictions between divergent organizational goals (regularity, profitability, reliability and safety) and keep the 'wheels' turning.

I side with Rasmussen (994: 22) where he states that 'rather than to aim at the control of errors, we should seek to control adaptation so as to move into a more safe practice'. This is where the challenge is. How can you control the migration in your practice when a) you don't know whether the drift that you consider to be uphill in terms of fitness, or b) towards lower-energy/cost states when choices are equal in terms of fitness, is c) also a drift towards the boundaries where failure is imminent, perhaps not in the selection environment constituted by the formal QA procedures, but in a physical selection environment further downstream?

Rasmussen speaks of the migration being subject to gradients, an effort gradient and a cost gradient. In NC there is no evidence of consistently choosing the options requiring the least effort. In an environment in which every working hour has to be accounted for, effort and cost are not far apart. Time budgets translate directly into economic costs influencing the profitability of the project. The transfer of 29,9 % of Statoil's share in the Sleipner license to the 'direct financial interest of the Norwegian state', the drop in oil prices and offshore cash flow and profit margins, combined with the tight time schedule due to the pre-arranged contracts on delivery of gas from a field that had not yet been developed, have produced in the case of Sleipner A a cost gradient. Although, I would rather call it a *regularity gradient*, because it is produced by our energy intensive societies' requirements for a regular production and delivery of fossil fuel energy sources; and our economy's craving for quick returns on investments. Perhaps it is better to say that in a commercial and competitive field as the offshore industry, a regularity gradient is always present. The 1985/6 drop in oil prices increased the gradient: it made the slopes of the energy landscape on which Sleipner A was moving steeper, influencing the selective environment in NC and Statoil in the sense that cost-reducing adaptations would be favored even more, and that cost-enhancing proposals would find it even harder to survive. In terms of a fitness landscape, the shape of the fitness hill that Sleipner was climbing became narrower with steeper slopes, increasing the system's or project's *vulnerability*. On these steeper slopes deviations away from a virtual optimum would have greater impact in terms of the systems ability to cope with the unpredictable consequences of adaptive changes in the geometry of tricell models. These unpredictable consequences were rooted in the software's inherent uncertainty and in the method's approximate nature. Early design decisions to remove the mechanical outfitting of tricells – resulting in an open hole in the top dome – robbed the system of its ability, or better, the possibility to recover from the crack formation in the tricell/shaft wall.

The relationship between the deteriorated economic climate and Sleipner's failure is not straightforward. It was not a simple trade off between reliability and profit. NC wasn't cutting corners. Yet, the resonance between solutions that were considered sound and smart by engineers with the project management's concern about budgets and profitability, produced an environment in which more cost-effective solutions would be valued, credited and rewarded positively, even more so after the 1985/6 drop in oil prices. Resonance or correlation is, according to Marion (1999), the way in which an organization, or groups within an organization, map their environment and adapt to it. Drift, that was considered to be moving uphill, occurred not because management put pressure on the design team to produce cheap and substandard work. It occurred as a natural adaptive process aiming for excellent performance.

Can organizations monitor this optimization-induced drift along a regulatory gradient and develop mechanisms to control it and move towards reliable practices, as Rasmussen puts it? Here is a conundrum to which there are no easy answers. The paradoxical nature of the failure mechanism – failure through optimization with no errors being present in the primary process – requires a paradoxical approach. Snook formulates it pointedly in his study on the accidental shoot down of US Army helicopters by US Airforce F15 fighters over Northern Iraq (Snook 2000). 'Did you shoot down any friendly helicopter lately?' Did you loose any Condeep platforms lately? If the answer is NO, when your overall performance is up to standard, excellent perhaps, that does not imply that you have not drifted into a more vulnerable zone. Or that improved practices are equally reliable compared to previous projects, because your new ways of doing might be more vulnerable due to changes in the regularity gradient that have changed the fitness and energy landscape on which you are moving. Excellent performance should be the subject of intensive scrutiny. Question your basic assumptions about the sources of your success. Look for the ways in which you have become vulnerable, despite or perhaps due to your successes. For any quality control procedure these will be the hard cases. Try to identify the various levels of selection environments in your line of work. Try to assess the range in which they are selectively neutral and assess the extent to which they overlap.

There is another and related lesson we can draw from this account of the Sleipner A GBS Loss. Standards of good work emerge in and are particular to (the highly interactive network of people and companies that constitute) adaptive performance systems. We know from science and technology studies that there are no universal standards that are independent of situated practices. All knowledge and experience is situated. What companies that are performing well should do is have somebody venture into other situated practices actively searching for standards that are dissimilar from one's own; to question what is taken for granted at home.

7.3. Postscript: meeting contractual obligations / achieving performative closure

The loss of Sleipner A constituted a considerable set back in the Sleipner field development. Confident that the cause of the failure had been identified it was decided to build a new gravity base structure Sleipner A2 basically following the original design. Sleipner A2 was made thicker again and the details of the tricell corners were improved. The results of the global analysis were checked, ironically enough, by manual calculations. Full scale tests were conducted before entering into the next loading situation; a procedure that would never have survived in the pre-accident environment in which Sleipner A1 was designed. Apparently the loss of Sleipner A1 shaped a quite different fitness and energy landscape for Sleipner A2, protecting it from the direct influence of the regularity gradient. The decks were temporarily placed on dummy shafts so that the loading of the installation and accommodation modules could proceed. Fully completed decks were then mated to the new GBS. Statoil had to make adaptive changes to other offshore infra-structural projects (like the Zeepipe to Zeebrugge in Belgium) in order to secure gas that could replace the Sleipner gas. In 1992 Alert Gaart (1992), who now had moved on to the position of Statoil's project director on Sleipner, could - with confidence in the company's ability to achieve performative closure - state that:

It is my firm believe that we will meet our objective to provide the gas as committed by 1. October 1993.

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