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Integration by *Infrastructuring*: The Case of Subsea Environmental Monitoring in Oil and Gas Offshore Operations

Thesis for the degree of Philosophiae Doctor

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“Lo duca e io per quel cammino ascoso
intrammo a ritornar nel chiaro mondo;
e sanza cura aver d’alcun riposo,

salimmo sù, el primo e io secondo,
tanto ch’i’ vidi de le cose belle
che porta ’l ciel, per un pertugio tondo.

E quindi uscimmo a riveder le stelle.”

(Dante Alighieri – Divina Commedia, Inferno, Canto XXXIV, 133 – 139)

“The Guide and I into that hidden road
now entered, to return to the bright world;
and without care of having any rest,

we mounted up, he first and I the second,
till I beheld through a round aperture
some of the beauteous things that Heaven doth bear.

Thence we came forth to rebehold the stars.”

(Dante Alighieri – The Divine Comedy, Inferno, Canto XXXIV, 133 – 139)

Abstract

This thesis investigates the development of ICT solutions for performing real-time subsea environmental monitoring during oil and gas offshore operations. The research is based on a three-year case study of an international oil and gas company headquartered in Norway. The thesis is specifically focused on aspects of integration: how new tools, systems, and approaches are developed, and how existing ones are adapted to fit the existing systems and practices of the oil and gas company.

The thesis has three goals. First, it analyzes how real-time environmental monitoring emerges as a distributed, interacting, and interconnected sociotechnical network (information infrastructure). Second, it identifies how the company's initiatives are currently changing the representations of subsea environmental risk in remote and previously inaccessible areas like the Arctic region. Third, it reflects on the research methodology to address such a spatially distributed and long-term setting.

On the theoretical level this work aims to contribute to the field of Information Systems and, marginally, to Computer-supported cooperative work. It is also inspired by Science and Technology Studies. A theoretical framework is developed connecting contributions from these three streams of literature in order to characterize the co-evolution of environmental monitoring infrastructures and their phenomenon of interest, environmental risk. This evolving relationship shows that, on the one hand, the perception of environmental risk as a problem is affected by the integration mechanisms that generate new knowledge. On the other hand, new conceptions of environmental risk have consequences for the maintenance and upgrade of environmental monitoring infrastructures. I call this process *infrastructuring*.

The thesis provides a vivid empirical illustration of how the relationship between environmental risk and integration strategies unfolds in offshore environmental monitoring. By merging the theoretical framework and the empirical case, I argue in favor of a flexible understanding of the development of complex systems in organizational settings. Studies of infrastructure should account for the existence of pragmatic approaches to face persistent uncertainty and the fluid relationship between situated usefulness and a cross-geographical dimension. In line with existing debates in the literature, I demonstrate that the traditionally bounded distinctions of system design/development/implementation and of users/designers must be overtaken when studying infrastructures. On the methodological level, this thesis therefore advocates a deeper empirical analysis of the unfolding of infrastructures in organizational realities.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) in partial fulfillment of the requirements for the degree of Philosophiae Doctor (PhD). The PhD work was performed at the Department of Computer and Information Science, NTNU, Trondheim, under the supervision of Professor Eric Monteiro (main supervisor), Professor II Vidar Hepsø (co-supervisor), and Professor Jon Atle Gulla (co-supervisor). The PhD project was financed by the Center for Integrated Operations in the Petroleum Industry.

Part of the research work was conducted during visits to foreign institutions: the Institute for the Study of Science and Technology and Innovation (ISSTI) at the University of Edinburgh under the supervision of Professor Robin Williams, and the IT University of Copenhagen (ITU), under the supervision of Associate Professors Pernille Bjørn and Brit Ross Winthereik.

The thesis consists of an introductory section comprising seven chapters and an appendix with seven published/submitted papers:

1. Parmiggiani, Elena; Hepsø, Vidar (2013). *Pragmatic Information Management for Environmental Monitoring in Oil and Gas*. In Proceedings of the 21st European Conference on Information Systems (ECIS), Paper 65
2. Parmiggiani, Elena; Mikalsen, Marius (2013). *The Facets of Sociomateriality: A Systematic Mapping of Emerging Concepts and Definitions*. In Nordic Contributions in IS Research Lecture Notes in Business Information Processing, M. Aanestad and T. Bratteteig (eds.), Springer Berlin Heidelberg, pp. 87–103
3. Mikalsen, Marius; Parmiggiani, Elena; Hepsø, Vidar (2014). *Sociomaterial Capabilities in Integrated Oil and Gas Operations: Implications for Design*. In Proceedings of the 22nd European Conference on Information Systems (ECIS), Tel Aviv, Israel, June 9-11, 2014, Track 20, Paper 3
4. Parmiggiani, Elena; Monteiro, Eric; Hepsø, Vidar (2015). *The Digital Coral: Infrastructuring Environmental Monitoring*. Submitted to Computer Supported Cooperative Work (CSCW)
5. Parmiggiani, Elena; Monteiro, Eric (2015). *The Nested Materiality of Environmental Monitoring*. Submitted to the Scandinavian Journal of Information Systems
6. Parmiggiani, Elena; Monteiro, Eric (2014). *A Measure of 'Environmental Happiness': Infrastructuring Environmental Risk in Offshore Oil and Gas Operations*. Submitted to Science & Technology Studies
7. Parmiggiani, Elena; Monteiro, Eric (2015). *Environmental Sustainability: Implications for Green IS*. Submitted to Management of Information Systems Quarterly

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My first huge thank you goes to my supervisor, Eric Monteiro. You are an invaluable guide, inspiring reference, and role model for me. You have always believed in me, supported me, and taught me how to find my own way through this intense PhD, where you have been the best companion. You have seen a potential in me that I was not able to see myself, and for this I owe you my deepest gratitude.

For the same reasons, I also heartily thank my co-supervisor, Vidar Hepsø, who helped me to navigate in a completely new world and supported me every day. Thank you for always listening to me, for always finding the time for a chat, and for always making me smile.

Thanks to the both of you, Eric and Vidar, for accompanying me and for letting me discover this exciting research making me feel the luckiest PhD student.

I would like to extend my gratitude to my co-supervisor Jon Atle Gulla for his support during my project and for providing useful comments. In addition, I also thank Monica Divitini for her constructive advice and for our chats in the dungeons of IDI.

I also greatly enjoyed and benefited from the advice and support of Robin Williams, Pernille Bjørn, Brit Ross Winthereik, and David Ribes. Your suggestions and feedback have been an invaluable resource for framing my work as it is today.

Thanks to the Doil project members, in particular to Petter Almklov and Thomas Østerlie for giving me the opportunity to spend a lovely time in Studio Apertura and for our chats and discussions.

A very special thank you also goes to all my informants for turning my fieldwork into an amazing experience, in particular for their patience, for never letting me feel like an outsider, for granting me access to precious information, and, above all, for being my best teachers of Norwegian.

I also gratefully acknowledge the financial support and the generous travel grants provided by the Center for Integrated Operations in the Oil and Gas Industry that made this PhD activity possible.

I am also thankful to my friends, with a special mention to the present and past IDI gang: Stefano, Simone, Francesco, Max, Alessandro, Ilaria, and, last but not least, Ines.

Finally, thanks to my parents Giordana and Enrico, my brother Edoardo, and my grandparents for your support ever since I decided to move to Norway.

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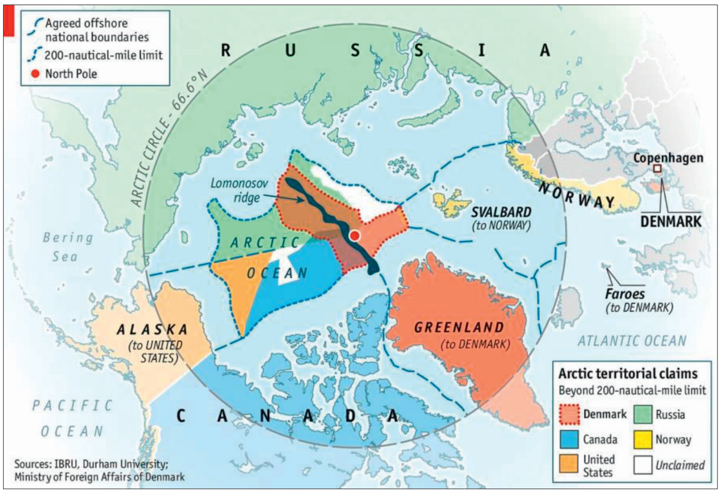
1 Introduction

1.1 Background and motivations

Offshore technologies in the oil and gas sector have developed at a steady pace in the last decade. New ICT architectures composed of fiber-optic data transfer, subsea sensor networks, and real-time alarm systems make it possible to achieve more efficient operations and move towards previously unreachable areas, such as deep-water oceans or the Arctic (Rosendahl and Hepsø 2013).

The Arctic region is a significant setting in which to study the expansion of offshore oil and gas operations (Figure 1). It is estimated that this area hides approximately 25% of the world's undiscovered oil and natural gas resources (Bird et al. 2008). Also as a consequence of the political turmoil in some of the world's petro-states (especially in the Middle East and Africa), the interest of oil and gas companies in Arctic drilling is today well-established, increasing controversy not only at the environmental but also the geopolitical level (Reegård et al. 2014). However, the subsurface Arctic resources have to date been almost impossible to access due to remoteness and harsh weather conditions. Although the melting of ice is now opening previously inaccessible waters, it is difficult to quantify the possible environmental impact of Arctic operations. As a consequence, the business relevance of the Arctic is counterbalanced by the strong uncertainties associated with the potential effects of oil and gas activities on the marine ecosystems (Blanchard et al. 2014; Hauge et al. 2014).



Sources: IBRU, Durham University; Ministry of Foreign Affairs of Denmark

Figure 1. Arctic territorial claims (Bender 2015).

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This unstable equilibrium is testified by the attention given to the theme of Arctic drilling by the mass media (see Figure 2 and Figure 3). For instance, in the US Royal Dutch Shell reportedly invested large amounts of money in the first half of the 2010s to seek permission to operate in offshore Alaska, facing stark opposition by the environmental organizations (Figure 2):

> "Shell is determined to drill for oil in the Arctic this summer [2015] if it can win the permits and overcome legal objections, although the energy company accepts *it will never win a battle with environmentalists over its reputation*. The oil group said the project would cost $1bn (£660m) *whether it proceeded with drilling or not*, given the fleet of vessels and other logistics that needed to be kept on standby." (Emphasis added)

Royal Dutch Shell

Shell determined to start Arctic oil drilling this summer

Petrol giant to ignore environmental protests and press on with $1bn project if it wins permits and overcomes legal objections

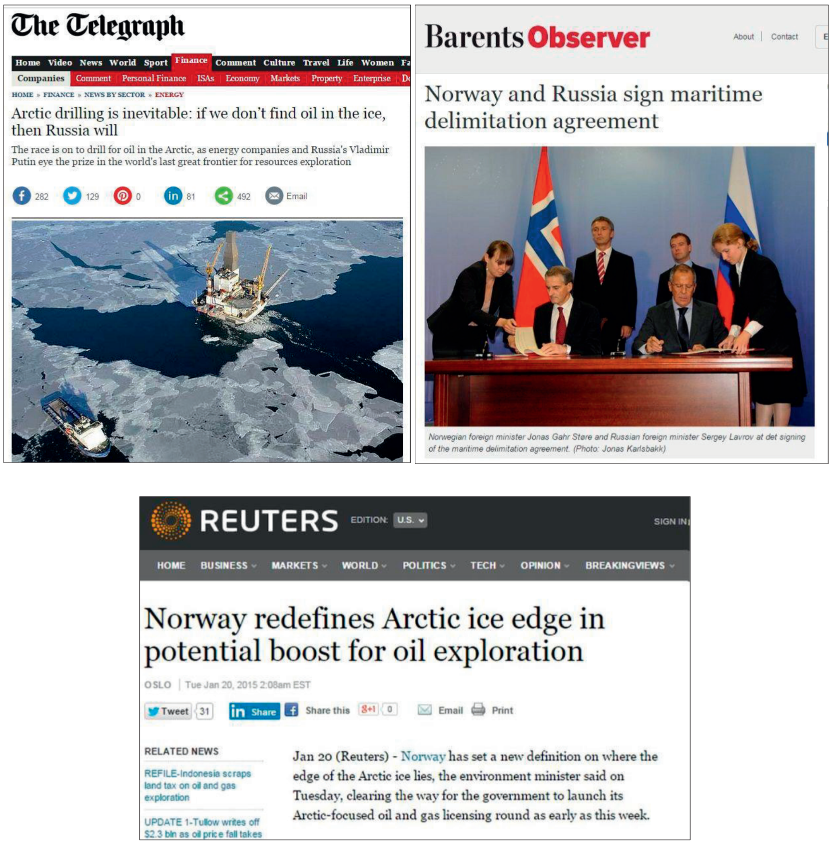
Terry Macalister and Damian Carrington

Thursday 29 January 2015 17.52 GMT

An aerial photo of the Shell oil rig at Kulluk, in the Beaufort Sea, Alaska, in 2012. Photograph: Gary Braasch/Gary Braasch/Corbis

Figure 2. Article reporting on Royal Dutch Shell's intentions to drill North of Alaska (Macalister and Carrington 2015).

Norway is another country bordering the Arctic where interest in the Arctic oil and gas has grown strong and is loaded with political meaning. In 2010 the country signed a treaty with neighboring Russia on maritime delimitation and cooperation in the Barents Sea (Figure 3). Two years later, the largest Norwegian oil and gas company signed a cooperation agreement with a large Russian state-owned operator. Finally, in 2015 Norway's government announced a northwards redefinition of the ice edge in its portion of the Arctic region, arguing that the ice has retreated for years and is now outside the areas that the government wants to award to oil and gas operators for resource exploration (Figure 3).



Arctic drilling is inevitable: if we don't find oil in the ice, then Russia will

The race is on to drill for oil in the Arctic, as energy companies and Russia's Vladimir Putin eye the prize in the world's last great frontier for resources exploration

Norway and Russia sign maritime delimitation agreement

Norwegian foreign minister Jonas Gahr Støre and Russian foreign minister Sergey Lavrov at det signing of the maritime delimitation agreement. (Photo: Jonas Karlsbakk)

Norway redefines Arctic ice edge in potential boost for oil exploration

Jan 20 (Reuters) - Norway has set a new definition on where the edge of the Arctic ice lies, the environment minister said on Tuesday, clearing the way for the government to launch its Arctic-focused oil and gas licensing round as early as this week.

Figure 3. Top left: a newspaper title reporting on the tensions around Arctic drilling (Critchlow 2014). Top right: article reporting on the Arctic border agreement between Russia and Norway (Nilsen 2010). Bottom: a newspaper article reporting on Norway's decision to redefine the ice edge (Koranyi 2015).

In sum, what appears to be an issue of subsurface resource exploitation is instead part of a much more intricate web involving economic, social, technical, and environmental factors.

Oil and gas companies are urged to seek solutions to achieve more efficient extraction of resources in inhospitable areas, to prevent harm to the marine environment, and, at the same time, to be engaged in a dialogue with the authorities and the general public to legitimize their operations. Among the approaches currently adopted are online remote access to information, reduction of data management fragmentation, integrated analytical systems, and the implementation of cross-disciplinary work processes (Reegård et al. 2014; Rosendahl and Hepsø 2013).

This thesis draws on a three-year case study to explore one large-scale effort in this direction by NorthOil[1], Norway's largest oil and gas company. NorthOil is currently engaged in a process to integrate technologies and methods for real-time subsea environmental monitoring in its daily operations (e.g., drilling, production, decommissioning). Among the problems faced by NorthOil are the choice of the technologies to deploy and their configuration, the assessment of which marine parameters to monitor, and how to turn the new datasets into risk calculations.

Norway is a relevant setting in which to study the interplay between technology development and environmental concerns: the oil and gas offshore sector is the largest industry in the country and accounts for more than 20% of the GDP, 15% of non-public workforce, and 50% of total exports (MPE 2014). These numbers make Norway one of the world's top exporters of petroleum and natural gas resources. The world showcases many constructs of wealth and oil, from South America to the Middle East. What makes Norway different is a balance between oil-centered capitalism and social welfare that is characterized by a history of collaboration among the operators, the unions, and the authorities and by the latter's strong regulatory activity to ensure the sustainable development of industrial activity (cf. Behrends et al. 2013). Controversies and disputes have however always accompanied the gradual expansion of the oil and gas activities from the first oil well drilled in the North Sea in 1969 to the recent expansion into the Barents Sea. Intense debates on the consequences of ice melting caused by global warming are today inflaming the Norwegian political landscape.

1.2 Theoretical approach

In this thesis I am investigating the integration of technologies and methods for real-time subsea environmental monitoring during daily oil and gas operations as a problem of *information infrastructure integration*.

The point of departure for this perspective is that large-scale networked ICT solutions like those used in the oil and gas industry cannot be studied through traditional approaches, assuming technology design and development as situated and time-limited (Monteiro et al. 2013; Williams and Pollock 2012). Complex ICT arrangements should rather be addressed as information infrastructures, i.e. distributed sociotechnical systems that aim to facilitate collaboration and coordination across geographical, disciplinary, and organizational boundaries over the long term, and that depend on an installed base of existing systems, norms, and practices (Bowker and Star 1999; Hanseth and Lyytinen 2010; Monteiro et al. 2013). As a result, the integration of new components in an infrastructure acquires a temporally and spatially unbounded nature. The theme of infrastructure is currently high on the agenda of Information Systems (IS) (Edwards et

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[1] All names of companies have been anonymized.

al. 2009; Monteiro et al. 2014) and Science and Technology Studies (STS) (Bowker et al. 2010; Edwards et al. 2013; Silvast et al. 2013). It is also a growing concern in Computer-supported cooperative work (CSCW) (Monteiro et al. 2013; Pollock and Williams 2010; Ribes and Lee 2010). Scholars within these fields recognize that this perspective brings not only a theoretical but also a methodological challenge for researchers. How should a shift from the study of 'systems' (often seen as artifacts) towards infrastructures be approached on the theoretical and, importantly, methodological level (Bowker and Star 1999; Monteiro et al. 2013; Ribes 2014a)? Consistently with my theoretical framework, I adopt and operationalize an infrastructural inversion (Bowker 1994; Bowker and Star 1999), a method to shift the attention from the work of the end users around particular tools, towards the broader and ongoing work required to maintain, repair, and upgrade the infrastructure as a whole. From this perspective some scholars thus propose to speak of information infrastructur*ing*, a transitive verb that blurs the distinctions between design, development, and maintenance, and describes the ongoing strategies of infrastructure designers and users to render the infrastructure useful to situated needs while remaining flexible for addressing uncertainties and future problems (Karasti et al. 2010; Pipek and Wulf 2009; Star and Bowker 2002).

Another tenet of this thesis is that the evolution of infrastructuring mechanisms goes hand in hand with the evolution of the objects these efforts ultimately attempt to tackle (cf. Bowker 2000). Infrastructuring more sustainable oil and gas operations therefore also entails a shift of perspective on oil and gas-related environmental risk. In general, the role of information systems in environmental sustainable processes is high on the IS agenda, under the label 'Green IS' (Boudreau et al. 2008; Malhotra et al. 2013). This attention is echoed in STS where it has been noted that an infrastructure metaphor is fruitful for conceptualizing the issues of expanding reach and size versus the local usefulness of energy infrastructures (Silvast et al. 2013).

I combine contributions in the infrastructure literature with insights from the fields of marine policy and pollution (Blanchard et al. 2014; Hauge et al. 2014) and the sociology of risk (Beck 1992; Jasanoff 1999) to describe the co-evolution of infrastructure and environmental risk as *integration by infrastructuring*. Along this trajectory, offshore activities are getting as close to environmentally sensitive marine environments as they ever have. The subsea life now becomes closely visible, online, and can be studied (cf. Latour 1999). How will the oil and gas industry develop infrastructures which not only integrate practices and systems, but which can also integrate with the natural environment? This question cannot be answered by looking only at the nature/technology interaction without taking into account that the encounter between oil and gas (and, more generally, industrial) interests and environmental issues opens ethical and political controversies about the very definition of environmental risk (cf. Beck 1992; Douglas 1992; Jasanoff 1999). 'Facts' about risk appear indeed to be negotiable and politically charged: How do we define pollution? As my case study demonstrates, little agreement exists in the first place about, for example, the effects of seismic surveys on sea mammals. My informants barely agreed on the comparability of subsea acoustic measurements taken from different positions. Nonetheless, infrastructure innovation also ends up accounting for antagonisms, it embodies decisions that are reached “in the face of persistent disagreement.” (Barry 2013, p. 7)

The theoretical framework is presented and discussed in Chapter 2.

1.3 Research setting and approach

The research presented in this thesis is based on a longitudinal (April 2012 – December 2014) interpretive case study conducted via an ethnographic method (Myers 1999; Ribes 2014a). The unit of analysis consists of the initiatives of an international oil and gas company (NorthOil) to establish real-time subsea environmental monitoring as part of daily operations. I look at the *infrastructuring* mechanisms, defined as the ongoing efforts to upgrade NorthOil’s infrastructure by integrating the new environmental monitoring capacities in the fabric of existing or adapted methodologies, technologies, and work processes.

In the last decade NorthOil has been involved in various projects to install online ocean observatories to track environmental parameters in several areas in different operational phases. I have investigated, in particular, the initiatives undertaken in areas where operations are today forbidden (offshore of the Lofoten Islands in North Norway), or where oil production is ongoing (offshore Brazil) or upon the drilling of a new subsea well (offshore central Norway). What is common to these locations is the presence of sensitive natural resources (coral reefs and spawning fish in Norway; calcareous algae in Brazil). With the goal of putting these experiences together and setting up an “integrated infrastructure for environmental monitoring” (sic), in 2011 NorthOil embarked on a three-year project in collaboration with three large project partners.

The research setting and approach are elaborated on in Chapters 3 and 4.

1.4 Research goal

The goal of this thesis is to make it easier to understand how the integration of environmental monitoring solutions unfolds and fits with the existing systems, practices, and standards of an oil and gas company. Since the study covered three years in a longer temporal span of innovation in the oil and gas business, I will mainly focus on the early stages of the integration process.

The main research question is formulated as follows:

What characterizes the early dynamics of the integration of an infrastructure for real-time environmental monitoring within the installed base of an oil and gas organization?

The main question is refined into the following three research questions:

1) **How does real-time environmental monitoring emerge as an infrastructure?**

2) **How is this process mirrored by a changed representation of environmental risk perception in an oil and gas context?**

3) **How can such a long-term and large-scale problem be addressed at the methodological level?**

The first question identifies **infrastructure** as the first and main theoretical theme addressed in this thesis. It aims to investigate analytically how the real-time environmental monitoring approach chosen by NorthOil takes the shape of an information infrastructure.

The second question addresses the mutual relationship between infrastructure development and changes to the representations of environmental risk perception within the oil and gas domain. In so doing, it defines **environmental risk** as the second theme of this thesis.

The third and last question is, instead, of methodological nature: How do we tell a large-scale story? I draw on the recent literature to reflect on how I – as an individual researcher – approached the study of infrastructure – something which is hardly physically delimited and develops over a long temporal span. In so doing, I operationalize the concept of **infrastructural inversion** (Bowker and Star 1999).

1.5 Contributions

Following Walsham's (1995) suggestions about how to generalize from an interpretive study, this thesis aims to contribute to IS – and partly to CSCW and STS – in three ways:

- First, the thesis provides a *rich empirical insight* into how environmental risk prevention systems and practices emerge and are integrated in the politically and economically loaded oil and gas context. I describe this trajectory through the concept of infrastructuring.

- Second, the thesis aims to contribute theoretically by presenting a cross-disciplinary *theoretical framework* to characterize some core aspects of infrastructuring. In so doing, it argues in favor of a flexible approach to the definition and connotation of information infrastructures.

- Finally, the thesis also outlines a set of *specific implications* for (i) theory and (ii) conducting empirical research on information infrastructures. I then conclude with reflections on the governance of information infrastructures.

In particular, the three stated research questions are answered as follows:

1) I provide a characterization of early-stage infrastructure evolution through the lens of infrastructuring which I intend as an ongoing, practical enactment where traditional distinctions of design/development, user/designer are overtaken. The answer to this question describes infrastructure integration as only emerging pragmatically and elaborates on the usefulness of a vague notion of infrastructure on the theoretical and empirical level. In addition, it problematizes established conceptions of installed base in studies of infrastructures. Finally, the answer to this question has implications for the Green IS research agenda.

2) My answer is again analytical and looks at how representations of environmental data and the associated risk emerge to balance tensions between situated problems and global requirements. In addition, I reflect upon the impact of environmental risk perception on infrastructure integration strategies.

3) My answer to this question draws upon an extensive discussion of my ethnographic method for conducting research on infrastructure, and a theoretical discussion of the notion of infrastructural inversion. In so doing, I provide reflections on the data collection design and process and on the definition of the case study so as to face a situation where spatial and temporal (and linguistic!) boundaries are not pre-defined.

In-depth answers to Research Questions 1-3 appear in the following papers (numbered for easy referencing):

Paper 1. Parmiggiani, Elena; Hepsø, Vidar (2013). *Pragmatic Information Management for Environmental Monitoring in Oil and Gas*. In Proceedings of the 21st European Conference on Information Systems (ECIS), Utrecht, The Netherlands, June 5-8, 2013, Paper 65

Paper 2. Parmiggiani, Elena; Mikalsen, Marius (2013). *The Facets of Sociomateriality: A Systematic Mapping of Emerging Concepts and Definitions*. In Nordic Contributions in IS Research Lecture Notes in Business Information Processing, M. Aanestad and T. Bratteteig (eds.), Springer Berlin Heidelberg, pp. 87–103

Paper 3. Mikalsen, Marius; Parmiggiani, Elena; Hepsø, Vidar (2014). *Sociomaterial Capabilities in Integrated Oil and Gas Operations - Implications for Design.* In Proceedings of the 22nd European Conference on Information Systems (ECIS), Tel Aviv, Israel, June 9-11, 2014, Track 20, Paper 3

Paper 4. Parmiggiani, Elena; Monteiro, Eric; Hepsø, Vidar (2015). *The Digital Coral: Infrastructuring Environmental Monitoring*. Submitted to Computer Supported Cooperative Work (CSCW) (under review after first round revisions)

Paper 5. Parmiggiani, Elena; Monteiro, Eric (2015). *The Nested Materiality of Environmental Monitoring.* Submitted to the Scandinavian Journal of Information Systems (under review after second round revisions)

Paper 6. Parmiggiani, Elena; Monteiro, Eric (2014). *A Measure of 'Environmental Happiness': Infrastructuring Environmental Risk in Offshore Oil and Gas Operations*. Submitted to Science & Technology Studies (under review)

Paper 7. Parmiggiani, Elena; Monteiro, Eric (2015). *Environmental Sustainability: Implications for Green IS.* Submitted to Management of Information Systems Quarterly (under review)

Table 1 outlines the relationship between the research questions and the papers and thesis.

Results are presented in Chapter 5 and discussed in Chapter 6.

Table 1. The relationship between the research papers, thesis, and the research questions addressed. The dot is bracketed if the question is only partially answered in the paper. The label under each paper is the field of contribution (IS; CSCW; STS).

	RQ1 **Information infrastructure**	**RQ2** **Environmental risk**	**RQ3** **Infrastructural inversion**
Paper 1 [IS]	●		
Paper 2 [IS]			(●)
Paper 3 [IS]	●		
Paper 4 [CSCW]	●	●	●
Paper 5	●		

[IS]			
Paper 6 [STS]	●	●	
Paper 7 [IS]	●	●	
Thesis	●	●	●

1.6 Structure of the thesis

This thesis is structured as follows.

Chapter 2 discusses the literature on the key themes addressed by this thesis and draws the overarching theoretical framework.

Chapter 3 presents the details and the historical background of the case study.

Chapter 4 elaborates and explains the research method adopted.

Chapter 5 presents the results by describing the articles attached to this thesis in the light of the theoretical and methodological insights of the whole thesis.

Chapter 6 draws the implications of my work for the three theoretical themes of this thesis and for infrastructure governance.

Chapter 7 contains the concluding remarks and some suggestions for future work.

The **Appendix** contains the seven research papers in full length and the co-authorship statements.

2 Theoretical approach

Stemming from the research questions introduced in Chapter 1, this thesis presents a theoretical framework based on two key theoretical themes and a third cross-cut methodological insight used as a means to approach the first two themes (see also Figure 4 for the schematic representation of their relation). The first theme, *environmental risk*, is empirically motivated and frames the general problem underlying this work. The second theme, *information infrastructure*, is proposed as a lens through which to address the tensions and complexities that are related to environmental risk management. The infrastructure-based perspective allows me to adopt and elaborate the concept of *infrastructuring* to describe the integration of environmental risk management solutions with the existing systems and practices of oil and gas operations as an ongoing work of maintenance, upgrade, and repair, rather than as a confined process of design and development. This conceptualization relies on the perspective of *infrastructural inversion*, which spans the first two themes and is cardinal to both the theoretical framework and the methodology (as discussed in Chapter 4). I frame infrastructural inversion as a resource both for the actors and the researcher (i.e., myself) to move the attention from the relations between end users/artifacts, towards the infrastructure that sustains and enables many interconnected relationships.

This chapter has two goals. First, it demonstrates that there is (at least partial) overlap in the themes of environmental risk and information infrastructure/infrastructural inversion. Second, the chapter positions the key concept of this thesis (infrastructuring) at the intersection of the three themes.

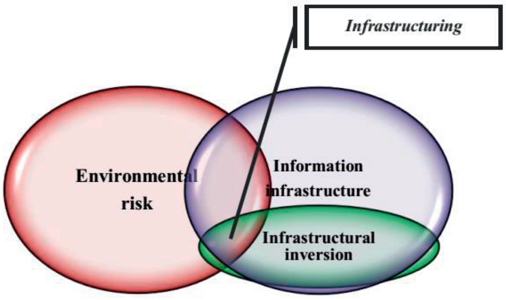


Figure 4. The relationship among the three theoretical themes. The size of the bubbles does not reflect the size of the domains considered. It however acknowledges that the literature on infrastructural inversion is a subset of the one on information infrastructure.

In the next sections I review the way that these topics have been developed by scholars in IS, CSCW, and STS. Despite the convergence in focus, the way they are addressed in each of the three camps is characterized by divergence.

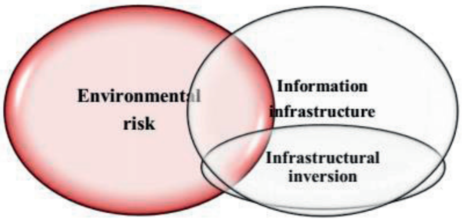
2.1 Environmental risk

I am interested in discussing aspects of environmental sustainability in this thesis, particularly related to environmental risk management. Companies and environmental agencies are increasingly adopting environmental risk as one of the main organizing principles of their activities. Environmental risk assessment methodologies are developed to quantify an organization's environmental impact and flag it as an organizing principle for their actions in the face of uncertainty. The translation of environmental sustainability into the language of risk management has become a constitutive feature of corporate governance to date, where the underlying idea is that well-governed companies are those able to handle environmental risks properly (Jasanoff 1999; Power 2007).

The relationship between *uncertainty* and *risk* is thus a cardinal one to understand the move of oil and gas companies towards the unexplored Arctic. Power's (2007, p. 6) interpretation permeates my theoretical approach:

> "Uncertainty is therefore transformed into risk when it becomes an object of management, regardless of the extent of information about probability (…) When uncertainty is organized it becomes a risk to be managed."

As a starting point, I specifically focus in this section on how the definition of environmental risk in the face of uncertainty has been problematized in the fields of marine policy, sociology, and IS.



2.1.1 The complex nature of environmental risk: Insights from marine policy literature

There is a rich body of literature in marine policy, maritime studies, and environmental science that investigates environmental risk in terms of the uncertainties associated with current risk assessment methodologies – in particular those in use by the oil and gas industry (Blanchard et al. 2014; Hasle et al. 2009; Hauge et al. 2014; Knol 2011). Even if not influenced by IS research, these studies highlight two relevant points that I draw upon in this thesis and that are also relevant to IS. First, these studies recognize that the uncertainty is due to a complex network of value-laden relations. Second, the focal role of the variability of the materiality of technologies and natural elements is recognized.

Hauge et al. (2014) note that the uncertainties embedded in risk assessment methodologies might lead to a failure to account for, for example, the long-term effects of an accident or the impact of minor oil spills on less commercially relevant natural species. The sources of such uncertainties often involve the material conditions of a specific site: geological and natural conditions, technical developments, and the characteristics of the marine species considered. As an example that echoes the case of this thesis, fish species with a swim bladder are more exposed to oil spills because they need to routinely surface in order to fill their bladders with air (ibid).

The sources of uncertainty arguably have an epistemological nature: they depend on ignorance or inconclusive knowledge which generates conflicts between the stakeholders involved in risk assessment procedures, notably the oil and gas industry and the fishery sector (Blanchard et al. 2014). Nevertheless, the complexity of risk assessment is recursive: "including more detailed information will introduce new layers of uncertainty." (Hauge et al. 2014, p. 86)

Uncertainty also emerges in the delicate moment of deciding the scope and practices of risk assessment when there is loose or no reference to comprehensive governance frameworks. In the recent years there has been attention paid in the literature to the ecosystem-based management of marine areas as a way to measure the quality of the environment (Knol 2013). From an actor-network theory basis, Knol explains the making of environmental governance as a process to construct nature as readable and relevant through the co-production of measuring instruments. This implies that an ecosystem is never unambiguously defined, but that facts about nature are constructed through categorization processes that are fed into governance where financial motivations might not necessarily overlap with political interests (Knol 2011).

The consequence of the uncertainties associated with risk assessment is thus that, upon closer scrutiny, they reveal that the final decisions made on risk assessment scope, method, and presentation are "more a value question than a scientific question" (Hauge et al. 2014, p. 88; see also Blanchard et al. 2014): uncertainties can be a powerful political tool. For example, based on the same seismic surveys, the oil and gas industry speaks in terms of their short-term 'viability', whereas the fishermen speak of the 'vulnerability' of the fish stock over the long term (Blanchard et al. 2014). As a result, different framings lead to different risk perceptions by the public audience.

2.1.2 Environmental risk and the role of materiality: Insights from the social sciences

The social sciences have long recognized that socio-political elements are cardinal, together with the scientific ones, in understanding the uncertainties associated with the definition and perception of environmental risk. Within the sociology of modernity and risk, uncertainties are treated as a condition of society (Beck 1992).

In his sociological theory of the risk society, Beck (1992) describes risk not as a consequence of the outside natural world, but rather as a consequence of human knowledge about it. Framed in this way, human knowledge provides "the means – the categories and the cognitive equipment – to recognize and present problems as problems at all, or just not to do so," (ibid, p. 163) and to overcome those same threats.

In his commentary on Beck's work, Latour (2003, p. 36) compares the concept of risk to that of network, as intended in his own actor-network theory:

> "As to 'risk', it does not mean that we run more dangers than before, but that we are now entangled, whereas the modernist dream was to disentangle us from the morass of the past. A perfect translation of 'risk' is the word network in the [actor-network theory] sense, referring to whatever deviates from the straight path of reason and of control to trace a labyrinth, a maze of unexpected associations between heterogeneous elements, each of which acts as a mediator and no longer as a mere compliant intermediary."

Throughout this thesis I will adopt the term 'risk' from this perspective.

As the marine policy literature told us, knowledge about the environment is not independent of political and social values. It is the result of a process of construction where it is impossible to place scientific analysis and political deliberations in separate compartments: "Uncertainty about the environment, in particular, increasingly appears as a very special form of politics." (Jasanoff 1999, p. 144) Environmental risk assessment practices indeed hide tacit assumptions about causalities and agencies that depend on each situated social order (Douglas and Wildavsky 1983); however, "[t]ranslating 'uncertainty' into formal quantitative language washes out the concept's cultural and political origins." (Jasanoff 1999, p. 144)

When risk is considered an epistemic problem, external agencies are removed and risk becomes reflexive (Beck 1992). The term 'reflexive' has to be interpreted, according to

Latour, in the sense that risk is generated by the reverberation of the unintended consequences of actions throughout society so that they become intractable (Latour 2003). In this sense, the complexities of risk assessment methodologies are sociotechnical, in that they demonstrate the interdependence between technological systems and social institutions (Barry 2013). These two elements – in the shape of public representations of risk resulting from formalized assessment methodologies and what can be measured given the existing capabilities – are however often misaligned (Kuchinskaya 2013). Latour (2005) elaborates on the sociotechnical – or rather sociomaterial – nature of risk by demonstrating that the fact that also objects have agency is one of the principal source of uncertainty. An epistemological understanding of Latour's actor-network theory considers human and non-human elements on the same level in constituting collectives. The consequence of this statement is therefore that the role of materiality should be acknowledged as performative of the construction of assessment and perception of risk. As I discuss in Chapter 4, this perspective has methodological implications.

To summarize, although from different yet sometimes connected angles, the literature within marine policy and the social sciences has developed an understanding of environmental risk not as an uncontested 'fact', but as the result of a process of construction where knowledge-related uncertainties reveal social, political, and economic agendas and heterogeneous elements compose dynamically evolving 'networks' (Latour 2003). A second relevant aspect is that, away from deterministic accounts of technology development, this perspective exposes the active role of the materiality of technologies and natural elements in shaping the construction of risk.

2.1.3 Information Systems and environmental risk: Green IS

To bridge the vast issue of environmental sustainability with IS, a research stream under the label 'Green IS' has appeared in the last six-seven years with a focus on the development of systems aimed at environmentally sustainable processes (Malhotra et al. 2013). According to Watson et al. (2008), Green IS is grounded on a change of paradigm: instead of making efforts to reduce the energy required to operate a specific technology, Green IS is meant to lead to the design and development of entire systems that are more sustainable.

Green IS research, however, is still in its infancy. Insights into how to design such information systems to enable a transition towards sustainability are lacking (Malhotra et al. 2013; Melville 2010). Some relevant studies have recently been published. Seidel et al. (2013), for example, propose key affordances of systems to allow environmentally sustainable work practices based on a case study from a software solutions provider. As Malhotra and associates note: "We should also be mindful, however, of Henry Ford's apocryphal admonition, 'If I had asked people what they wanted, they would have said faster horses'." (p. 1268) The development of environmentally sustainable solutions might be in the hands of a few and lightly bounded initiatives.

Another interesting study was conducted by Marrett et al. (2013), who underlined, on the one hand, the importance of considering and aligning financial and environmental goals to reduce CO_2 emissions, and on the other hand, they noted on the relevance of normative pressures when financial gains are still difficult to predict. Malhotra et al. (2013) make two points that are also relevant for this thesis when commenting on this article. Information has both a rational and a social dimension that "we can also think of as the interplay between prices and perceptions (Watson et al. 2012)." In particular, we should investigate the way the presentation of information might favor specific perceptions regarding environmental sustainability. In addition, "one major shortcoming of the IS academic community, we contend, is its general failure to influence mass change through participating in the formulation of industry standards and government policy. We need to discover how we can insert ourselves into these processes so that IS-related outcomes will create pressures for desirable ecological change." (Malhotra et al. 2013, p. 1269)

2.1.4 Summary

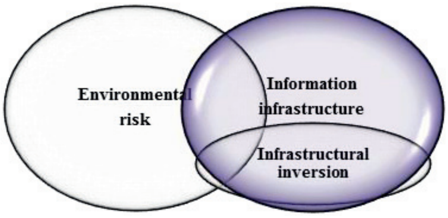
In summarizing the above sections, three key points emerge:

- *Environmental risk perception*. The IS field should address more efficiently not only the rational but also the social dimensions involved in the realization of environmentally sustainable systems. In this way, we can specify that what we are dealing with is not 'environmental risk' as an independent entity, but rather its *perception*.
- *The networked nature of environmental risk.* The analysis of the uncertainties associated with modern risk assessment methodologies, as a byproduct, problematizes the notions of environmental risk on the spatial and temporal level. 'Risk' is the result of networked, distributed, and long-term relations between social, technical, and natural elements. Its analysis therefore deserves a theoretical concept able to fully account for the dynamic nature of these relations. To anticipate the language I will adopt later, environmental risk should be analyzed in terms of its infrastructural nature.
- *The materiality of environmental risk*. Among the sociomaterial relationships that entwine to generate a particular conception of environmental risk, those involving material components deserve a closer scrutiny because they are constitutive of risk as a phenomenon and of the methodologies used to assess it.

I now turn to describing the theoretical concept that offers a basis for explaining how the design, implementation, and maintenance of information systems can approach the complexities of environmental risk and the uncertainties it enfolds.

2.2 Information infrastructure

As introduced in Chapter 1, new technologies have recently been adopted in environmental risk assessment. Metaphorically, such instruments act as prostheses: they give access to previously inaccessible locations – e.g., the seafloor – with increasingly shorter temporal gaps – e.g., in real time. However, technologies per se do not solve but rather pose new problems related to the management, analysis, and interpretation of the new data. As a consequence, for environmental risk assessment to be conducted, the new instrumentation must be embraced in new organizational forms – where ‘organizational’ encompasses the development of new practices, computational systems, standards, and expertise, and entails the creation of economic interests and the redistribution of labor (Edwards et al. 2013). We therefore need a powerful concept to describe these elements and address the ‘entangled’ nature of risk (Latour 2003, 2005). For this reason, I propose to adopt information infrastructure.



2.2.1 Defining infrastructure

Born as a military term to designate fixed facilities, the concept of infrastructure has evolved greatly since the mid-1990s, in particular since Hughes’ seminal study of large technical systems (Hughes 1993; cf. Jensen and Winthereik 2013; Edwards et al. 2009).

Within STS, studies of infrastructure are more than two decades old. A key conceptualization of infrastructure, which underpins almost all the following contributions, was first given by Star and Ruhleder in CSCW (1994) and later in STS (1996). They define infrastructure in terms of organizational and social arrangements encompassing not only heterogeneous technologies, but also standards, classification systems, routines, and norms. This notion is useful to understand the relational and historical nature of infrastructure, which cannot be conceived of as a thing, but rather as a relational concept: infrastructure becomes such in relation to organizational practice, and emerges when local practices are afforded by large-scale solutions (Star and Ruhleder 1996).

The European and the American research fields have followed parallel paths in pursuing infrastructure studies. European scholars have developed the concept of *information infrastructure* to describe large-scale integrated information and communication technologies in the workplace (Monteiro et al. 2013). The rhetoric drive of the concept was inherited by the European Union's initiatives and policies promoting the development of an information society in light of the "Information Age." Cardinal in this respect was the Bangemann report to the European Council (Bangemann 1994) advocating interconnected and interoperable systems and standards to foster the emergence of new sectors of the economy and new Europe-wide markets for information services (see also Hanseth et al. 1996). The Bangemann report also clarifies that information infrastructure initiatives should come from the private sector and leverage the capital available to the emerging telecommunication market segment. The availability of rich case studies on the realization of more efficient interconnected systems and standards was also fundamental to the development of the field. Influential studies have been conducted about the development of the Internet (e.g., Hanseth and Lyytinen 2010; Monteiro 2000). Other preferential settings have been the health care sector (Ellingsen and Bjørn 2014), industry (Ciborra 2000; Østerlie et al. 2012), quality certification (Monteiro and Rolland 2012), and recently finance (Kaniadakis and Constantinides 2014). Of relevance to this thesis, the oil and gas domain has been the object of studies, particularly in Northern Europe, owing to a work environment which is arguably more open to external researchers (Almklov et al. 2014; Monteiro and Hepsø 2002; Østerlie et al. 2012).

In general, the influence of actor-network theory on the conceptualization of information infrastructures as assemblages (Monteiro 2000) or networks of human and non-human elements has been considerable (Hanseth and Monteiro 1998). Monteiro and Hanseth (1996) explain: "Intuitively, as [actor-network theory]'s primary object is to describe technological systems and non-technical structures as single units, i.e. as *socio-technical networks*, it should be well suited for describing interrelations between network organizations and network technologies." (Emphasis added)

In the US, researchers of infrastructures have followed a slightly different path, not always communicating with their European counterparts until recently (Edwards et al. 2009). The National Science Foundation offered funds to develop integrated solutions supporting interdisciplinary scientific data sharing, particularly in the earth sciences. Following the Atkins (2003) report, such infrastructures have been termed 'cyberinfrastructures' (e.g., Ribes and Lee 2010). In a nutshell, cyberinfrastructure was a unitary movement to promote the attention to technology, data exchange, and instrumentations. Comparable studies have also been funded in the UK since the early 2000s under the label 'eScience' and later also 'eResearch' to encompass the study of computing infrastructures for collaboration in the humanities and in academic settings (Jirotka et al. 2013).

Empirically, despite the grand intentions of cyberinfrastructure initiatives, American researchers have identified how matters of space and, in particular, time, generate tensions that often hinder or prevent the development of infrastructures, for instance between national institutions and the local enactments of technology (Ribes and Finholt 2009). Whereas the actor-network theory tradition of information infrastructure studies considers humans and non-humans as equally participating in shaping action (Latour 2005) – at least on the epistemological level – cyberinfrastructure research tended to dampen the "human factor" in favor of the technological aspects. In the second half of the 2000s, scholars demonstrated the importance of human and organizational arrangements in cyberinfrastructure development (e.g., Bietz et al. 2010). Such contributions emphasized the need to analyze infrastructure projects as always molded by an installed base that encompasses not only artifacts and technologies but also human practices, regulations, and shifting power relations (Edwards et al. 2009). In particular, critical of the lack of focus on the social aspects (intended as people and labor) of knowledge development in cyberinfrastructure, Edwards et al. (2013) propose to bring the knowledge element back, and speak instead of *knowledge infrastructure*, defined as an interconnected, modular, and rough-cut robust network of people, institutions, and tools whose primary target is to "generate, share and maintain specific knowledge about the human and natural world." (ibid, p. 17) From this perspective, according to Edwards and associates, we should understand infrastructures and hybrids rather than the sum of social and technical elements.

We are then left with two notions – information infrastructure and knowledge infrastructure – which are sometimes used interchangeably but also preserve their differences. In addition to the evident focus on the flow of information in the workplace on the one side and on the sharing of scientific knowledge on the other side, these concepts in general have different normative (public vs. private incentives), empirical (industry and health care vs. environmental research), and theoretical (e.g., actor-network theory vs. grounded theory-based approaches) heritage. While this characterization is not clear-cut and exceptions exist, these differences are there for good reasons – e.g., there are different public spending cultures in the US and the EU and different privacy and confidentiality requirements in the US, the UK, and the EU which shape the way infrastructures unfold and access to cases is granted (e.g., to oil and gas companies). These factors, together with the theoretical underpinning, affect what is visible to researchers – for example, the efficient flux of information in an oil and gas company contra the generation and preservation of knowledge about sea water pollution.

Interestingly however, these two different camps have recently been converging by organizing joint workshops[2] resulting in special issues of renowned journals (Edwards et al. 2009; Monteiro et al. 2014). As a result of this brief outline, the two notions still imply different emphasis, but they are moving towards developing conceptual similarity, grounded on, for example, the highly influential work of Susan Leigh Star (Bowker and Star 1999; Star 1999; Star and Ruhleder 1994, 1996).

The scaffolding of this thesis is both information infrastructure and knowledge infrastructure. However, I primarily rely on an IS-based understanding of *information infrastructure* informed by actor-network theory. I mean infrastructures as complex, distributed sociotechnical networks characterized by openness in terms of types of users, interconnected and dynamically evolving systems underlying multiple agendas, and shaped by an *installed base* comprising existing practices and systems (Monteiro et al. 2013). Information infrastructures emerge as a precarious equilibrium of multiple interlocking systems and processes where local fitting entails unfitting at other sites and components entangle with others that are apparently unrelated (Monteiro and Rolland 2012).

Due to the empirical case study I followed, I am also influenced by the lens of knowledge infrastructure, in particular by Edwards et al. (2013), whose definition of knowledge infrastructure aims to shed more light on the organizational changes associated with technology innovation which are rarely socially, culturally, and economically neutral. After all, infrastructures are as unpredictable as the natural phenomena they attempt to govern (Ciborra 2000), such as global warming (see also Edwards 2010). They are as fundamentally vague ontological entities where "tools and technologies are never independent of the actors and organizations that promote, maintain, and use them." (Jensen and Winthereik 2013, pp. 12–13) It is therefore convenient to exploit the vagueness of infrastructures, because it empirically constitutes the condition of their workability and conceptually makes it possible to cut across and explore different definitions.

2.2.2 From situated actions to (socio)materiality: Accounting for the materiality of infrastructures

The studies of organizational work arrangements within CSCW and IS have so far often privileged the localized, situated appropriation of technological artifacts by the end users (Monteiro et al. 2013). One of the reasons for this strand of research is the influence of practice-based conceptualizations of technology enactment in work practice

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[2] Innovation in Information Infrastructures (III) workshops in Edinburgh (October 9th, 2012) and Oslo (October, 13th – 16th 2014)

(Schatzki et al. 2001) and of Suchman's (2006) notion of 'situated action'. Suchman's work has been particularly important in debunking overly structural accounts of work practices, and in highlighting that action is always situated in the sense of being "taken in the context of the particular, concrete circumstances." (ibid, p. 25-26) These studies have provided a powerful tool to analyze how the concrete circumstances of daily work practice differ from formal work processes and how the same technology is in fact appropriated differently in different context. For all their merit, critiques have been levelled at these studies because they have failed to account for the meaning of the qualifier 'situated', therefore overlooking the relationships between instances of work practice separated in time and space (Monteiro and Rolland 2012; Pollock et al. 2009). Among the reasons for this is the fact that such analyses are often the result of short-lived case studies which miss the temporal and spatial stretching of the infrastructure that in fact supports actions (Williams and Pollock 2012). Kallinikos (2004) observed that the study of technology cannot be exhausted by an analysis of the user/technology interface. Such a perspective cannot grasp the interplay between the specific contextual enactment of a technology and the network of technical, organizational, and social arrangements that sustain that technology. Modern infrastructures magnify a 'situated action' that is constituted across distributed (Pollock et al. 2009), trans-situated (Monteiro and Rolland 2012), and digital settings (Knorr-Cetina 2009). Examples include those disciplines which rely almost exclusively on computer-based representations and models to deal with objects that are physically inaccessible to humans. For example, Frodeman (1995) describes geology as a hermeneutic science because it is characterized by instrument-mediated access to the subsurface, a prejudgment about what the problem is and what will account as an answer, and a historical layering of goals and decisions that influence the direction of future research. Edwards (2010) offers a vivid illustration of how the infrastructure for climate data modeling has evolved in recent decades. Edwards demonstrates how models are tuned and adapted to obtain heuristically valuable predictions. They do not abstract or represent reality; they rather constitute it (see also Edwards 1999).

Computer models are thus an example of technology-mediated situations that cannot be physically bounded and emerge from intricate entanglements of the social and material aspects of infrastructures. They also explain the need for studies that detail not only that, but how technology – and, more broadly, materiality – shapes, or performs, the situation (cf. Barad 2003). This is the heart of the recent discourse in IS on *sociomateriality* (Leonardi 2012; Orlikowski and Scott 2008; Parmiggiani and Mikalsen 2013). Since the 1950s sociotechnical researchers have realized that technological innovation surfaces from both social and material aspects (Parmiggiani and Mikalsen 2013). It was however not until the 2000s that Orlikowski (2007) and Orlikowski and Scott (2008) brought together different theories and research streams (in particular actor-network theory (Latour 2005), Barad's (2003) agential realism, and, again, the work of Suchman

(2006)) into an agenda for organization studies that promoted the study of how the interplay between IT and organizational work unfolds in practice. As Østerlie and colleagues (2012) observe, the current use of the term can be traced back to Mol (2002) who posited that the social and the material are not given beforehand but *enacted through practice*. The implication of this, Østerlie et al. (p 88, emphasis added) continue, "*is that material reality is neither social nor material, but always part of the same performances: it is sociomaterial*. (…) Explanatory power, then, is not on the objects themselves, but on the relationship between the social and the material."

Sociomateriality implies what elsewhere has been called the 'ontological turn', namely a focus on practice not only as a set of social interactions but also of material enactments (cf. Woolgar and Lezaun 2013). This perspective, then, means everyday practice as "configured and reconfigured by multiple meanings and materialities that are fused together in the engineer's work." (Orlikowski and Scott 2008, p. 460; cf. Suchman 2006) A key notion of sociomateriality is *performativity* (Barad 2003), which relates to enactment (see also Mol 2002). According to Orlikowski and Scott (2008, p. 462):

> "…the notion of performativity draws attention to how relations and boundaries between humans and technologies are not pre-given or fixed, but enacted in practice. A practice lens is thus particularly helpful in grounding this notion of performativity."

In this sense, then, practice refers to the enactment of boundaries and relationships. There are two direct implications for the study of infrastructures.

The first relates to the inseparability of the infrastructure and what is visible and how. Infrastructures are inherently sociomaterial because they have an ontological implication: they define what can be known and therefore what can be done (Jensen and Winthereik 2013) by bridging undifferentiated nature and the quantified world of experts (Østerlie et al. 2012).

The second implication is that, if we take the definition of performativity seriously, we should avoid treating technological development and adoption as special cases of organizing processes. Instead, we should focus on how technology becomes incorporated into routine practices (Orlikowski and Scott 2008). Other approaches have instead pointed that moments like technology development and early adoption are an important opportunity to investigate how the entanglements emerge (Leonardi and Barley 2008). For the sake of this thesis, I will refer to the former approach.

In its practice-based tradition, sociomateriality research has productively focused on the interrelationships between computing technologies and the social context in which they are operated (e.g., the work of Suchman). If we consider the case of subsea environmental monitoring presented in this thesis, however, the unfolding of material reality embraces levels that go beyond in-office technologies and encompass remote sensing and real-world physical phenomena (e.g., fish migration). To date however, overcoming a representational view on materiality and unpacking its performative role in practice has proven particularly problematic for researchers (Cecez-Kecmanovic et al. 2014; Monteiro and Hanseth 1996). To leave behind the impasse and obtain a better insight into the ontological stance of infrastructures, we propose to focus specifically on how materiality performs in practice (e.g. the subsea environment during a monitoring campaign). In Paper 5 we contribute the concept of 'nested materiality' to describe how material phenomena emerge as the recursive and purposeful nesting (or "fitting together") of the physical world and the infrastructure that makes them possible through hardware and modeling tools. Nested materiality expands studies on performativity (Kallinikos et al. 2013; Østerlie et al. 2012) and underlines the interactive nature of distributed and interconnected infrastructures. In other words, this notion shows how the infrastructure turns phenomena (e.g., the coral reefs in the Norwegian Sea) into something which is meaningful and relevant for one or more groups of users across different domains.

2.2.3 Perspectives on infrastructure integration

One of the implications of the previous paragraph is that innovation (e.g., introducing environmental monitoring capacities in oil and gas infrastructures) never builds on a clean slate (Star and Ruhleder 1996), but rather emerges from an underlying open-ended, spatially and temporally unbounded bundle of practices, existing systems, standards, and formal procedures to which the new components must be connected. The process of establishing such connections is one of *integration*. According to actor-network theory, integration efforts are complex sociotechnical networks where human and non-human actors engage in distributed processes of negotiation and improvisation (Latour 1987, 2005). Earlier sociotechnical studies of large-scale organizations clearly indicate that these processes are seldom the result of top-down business strategy. Ciborra (2002) presents the concept of bricolage as a design methodology based on virtuoso tinkering and improvisation by competent actors who leverage the resources at hand and diverge from the formalized ways of operating. According to Monteiro and Hepsø (2000) rather than a management-driven alignment, the relationship between technology development and business strategies is one of co-evolution or mutual construction. Hepsø et al. (2009) describe the process of introducing a new collaborative infrastructure for production optimization in an international oil and gas company as a transformative amalgam, or patchwork, of elements of the new infrastructure and the installed base. Their study is interesting for two reasons. It frames integration not as a deterministic process, but as a continuous tension between top-down institutional requirements for more global integration and bottom-up reliance on information generated locally by heterogeneous disciplines and devices. In so doing, it makes clear that the role of the installed base is more active than previous studies led us to imagine. The installed base is not an almost immutable layer on top of which infrastructures 'drift' (cf. Ciborra 2000), but is also reshaped as part of a *recursive* process of evolution, where local and global perspectives constantly flicker (Hanseth and Lyytinen 2010; Jensen and Winthereik 2013; Tilson et al. 2010). The recursivity of infrastructures has a dual nature: on the one hand, the more levels of mediation are added, the more complexity and uncertainties are introduced (Jensen and Winthereik 2013). On the other hand, these ongoing (re-)configurations are generative of new sociomaterial relationships and thus new opportunities to be explored (Tilson et al. 2010).

The object of study in this thesis is the realization of an infrastructure in its *early* stages. An important concept used to describe the early dynamics of infrastructure evolution is *bootstrapping*. In general, it has been proposed as a strategy to address the early dynamics of infrastructure initiation that acknowledges and attempts to capitalize on the top-down/bottom-up tensions. From an IS position Skorve and Aanestad (2010) present bootstrapping as an algorithm based on attracting a critical mass of users for direct usefulness when the use of the infrastructure is not yet formally mandated or economically subsidized. Most popular case studies are in health care or the development of the Internet. The premise of this approach is to begin with the simplest solution by enrolling a few initial users who may gain benefit without a larger network. This generates a chicken-egg problem for infrastructure designers, who must both meet the early users' needs and anticipate the completeness of their solution (Hanseth and Lyytinen 2010). The notion of bootstrapping was also adopted earlier in STS by Bowker (1994) as an empirically grounded and heuristic process to conjure a set of meaningful parameters from highly situated realities to ensure their inclusion in a global or standardized picture. In other words, this approach takes advantage of the tensions between local realities and a global infrastructure by creating a small-scale 'laboratory' (which in Bowker's account might as well stretch across thousands of miles) that confines the initial phase of trial and error until it is ready to increase its scale (Paper 4). Notwithstanding the resonance between these insights, in this thesis I lean towards the latter conceptualization of bootstrapping because of its open-ended and empirical character that better suits the specificity of the case study presented in Chapter 3. In sum, I define bootstrapping as a process by which to address the early dynamics of infrastructure integration by exploiting the local/global tensions and leveraging a few economically and politically strategic solutions in a delimited or situated reality, so that pragmatic relevance is visible (even if not necessarily overlapping) for a few key stakeholders.

These conceptualizations introduce one of the key points of this theoretical framework, which I will discuss later: that the development and integration of infrastructures is not a matter of clearly bounded design and development phases, but has a continuous and evolving nature (Paper 6). Two consequences follow.

The first consequence is one that has always been recognized by the actor-network theory tradition. The theoretical and practical dichotomy between local and global aspects is removed, making 'local' and 'global' concepts which depend on the relative point of view: the empirical strategy is thus to trace out where, how, and when the 'local' and the 'global' become interdependent (Ellingsen et al. 2013). For example, Almklov et al. (2014) studied the work of petroleum engineers and how they make sense of sensor-based data of subsurface reservoirs. The authors demonstrate how, by being 'global', the infrastructure becomes part of a particular 'local'. On the one hand, the work practices and the knowledge of the engineers are situated in the sense that they inextricably depend on the infrastructure to extrapolate sensor data. On the other hand, the infrastructure co-evolves with the work practices of engineers. As a consequence, the infrastructure, which per definition extends from the local settings, is part of the situated action of engineers (ibid).

The second consequence has to do with the temporal dimension of infrastructure development and will later bring us to the next theme of this thesis. As noted by Karasti et al. (2010), temporality deserves attention when investigating infrastructures. The aforementioned need to find new organizational forms that support the innovation of instrumentation must be mirrored by a form of research analysis that better responds to the change of temporal scales and rhythms involved in infrastructure evolution (Edwards et al. 2013). In general, current studies of infrastructure development indeed tend to fail to demonstrate how the different temporal perspectives of heterogeneous actors can coexist within infrastructure (Ribes and Finholt 2009; Williams and Pollock 2012). Some scholars, however, are becoming more sensible to this issue. For instance, Karasti et al. (2010) propose the notion of "infrastructure time" to blur the tension between design, implementation, and the use of infrastructure:

> "From the point of view [of] infrastructure development, infrastructures do not 'occur' in practice when developers are deliberately able to resolve the tension between short-term and long-term, although it may very well serve as a sound principle underlying infrastructure design strategies and methodologies. Furthermore, infrastructure development is not only an intentional activity, an emergent element is always—particularly over the long-term—involved. (…) [I]nfrastructure development implies working both with short-term and long-term timeframes, e.g. in answering immediate user needs and making data available to scientists through a local data system while also anticipating future needs or constraints and preserving data for archive or reuse." (p. 400-1)

Ribes and Finholt (2009) analyze the way that different temporal concerns correspond to different scales of infrastructure (technology development, work routines, and institutions). They adopt the “Long Now” as an organizing principle for infrastructure planning and maintenance that couples the definition of the problem space (mismatching temporal concerns) with the enactment of its solution: that infrastructure long-term sustainability becomes a short-term consideration.

Looking more closely at the way different temporal concerns mismatch and yet coexist enables researchers to understand how the “Long Now” happens in practice. Traweek (1987) richly illustrates how high-energy physicists develop a community through common world views. In Traweek’s account, temporal scales (or the way physicists experience time) are one of the key symbols of the physicists’ culture and become institutionalized by producing and reproducing work practices. Temporal scales may vary as the participants shape them based on changing circumstances. Understanding how temporal spans materialize in practice is important for infrastructure implementation: as I pointed out earlier (Parmiggiani 2014), in the case of oil and gas organizations the different disciplines operating a well follow different objectives with different time constraints: geologists look at reservoirs which evolve in terms of centuries, while drilling engineers have to operate in real time with parameters that are updated every second or minute.

Williams and Pollock’s (2012) “Biography of Artifacts” provides a framework by which to address both temporal and spatial dimensions to study the career of workplace technologies (or packaged enterprise solutions) by following the history of relationships and the sites implicated in their evolution. As I also note in Chapter 4, Williams and Pollock give a set of methodological recommendations to address the multiplicity of historical frames and locations involved.

The different spatial and temporal frames of the different communities call for an analysis of how infrastructures support computer-mediated collaborative work across distributed settings (Karasti et al. 2006; Ribes and Lee 2010). Many contributions in IS and organization studies have demonstrated that coordination and collaboration can be achieved in spite of actors’ heterogeneous perspectives. For example, Carlile (2004) presents the problem as one of knowledge sharing and proposes a framework where collaboration is deemed successful if it cyclically overtakes the syntactic, semantic, and pragmatic boundaries of the communication process. In this perspective, integration emerges as a process of negotiation between communities. Inspired by Berntsen (2011; cf. Donnellon et al. 1986), in Paper 1 (Parmiggiani and Hepsø 2013) we demonstrate that inter-community negotiation might be conducted only *equifinally*: only through pragmatic short-lived and situated articulation efforts. Jarulaitis and Monteiro (2010) point out that the need for tight integration might have been overstated. They present a case of system integration in an oil and gas company where lack of unity is not necessarily a problem: integration is achieved as an on-demand workaround. Their analysis is grounded on Mol (2002), who vividly illustrates how integration can take place without a shared and coherent ontology. She describes these efforts as *enactment*, ways to frame human and non-human elements as part of plays that are staged. Unity and a lack of controversy are never pre-conditions, rather, unity is a result of ad-hoc coordination work, and the relative lack of controversy is the result of distribution. This point of view resonates with Star and Ruhleder's (1996) key idea that infrastructure is both relational and practical. Integration efforts must take into account the fact that infrastructure always means different things to different groups of practitioners because it is deeply entangled into each group's activities, tools, and environment.

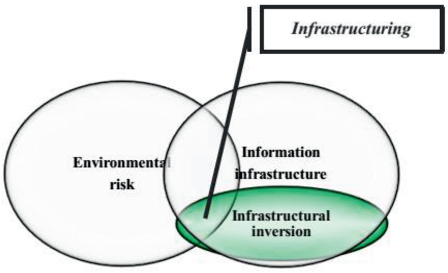
2.2.4 Summary

I highlight the following concepts to summarize the previous section:

- *The recursivity of infrastructure*. Infrastructure development through integration has a recursive nature because it supports the continuous emergence of new sociomaterial relations. In this process, 'local' and 'global' aspects are interdependent and different temporal scales get to coexist. The infrastructure's installed base is also constantly shaped as part of this recursive process.
- *Nested materiality*. The concept of nested materiality, drawing on the sociomateriality agenda, helps to show how phenomena which exist independently of the infrastructure are turned into meaningful and relevant for heterogeneous stakeholder groups.
- *Bootstrapping*. The early dynamics of infrastructure integration can be addressed as a process of bootstrapping, a strategy to capitalize on the top-down/bottom-up tensions of innovation. It leverages a few economically and politically strategic solutions in a situated realty so that direct usefulness is visible for a set of core stakeholders.
- *Performativity*. 'Objects' become real as they are made part of a practice and contribute to constitute reality.
- *Equifinal integration*. Integration can be the result of short-lived and pragmatic articulation efforts; the need for tight integration might have been overstated.

2.3 Infrastructural inversion and Infrastructuring

One of the core messages of the previous section is that infrastructures are always evolving, always being integrated with new capabilities. The time dimension of infrastructures is particularly of the utmost importance, ultimately because the time-limited studies of technologies (or artifacts) appropriation might overlook important aspects, actors, or places of technology evolution (cf. Williams and Pollock 2012). The last piece of the puzzle required to assemble this theoretical framework is a lens that provides the conceptual and methodological tools to overtake the shortcomings of the traditional studies of system development. I argue in the next section that *infrastructural inversion* is one such mechanism.



2.3.1 "From artefacts to infrastructures": From articulation work to infrastructural inversion

Monteiro et al. (2013) brought together the stream of research presented in the previous section and addressed a call to CSCW to re-conceptualize design and development in a way that better suits complex organizational arrangements. The authors describe the shift of perspective underlying this reconceptualization as a move "from artefacts to infrastructures":

> "Focusing exclusively on implementation and use, for instance, means that a range of (equally) important actors and factors in the shaping of a technology are relegated to the background. An [information infrastructure] perspective by contrast, would contribute by supplementing a local view with what might be thought of as an 'extended' design' perspective to capture how workplace technologies can be shaped across multiple contexts and over extended periods of time." (p. 576)

CSCW has adopted the concept of *articulation work* from sociology, where it was coined by Strauss (1985) to describe work to sustain the division of labor. Within CSCW it came to indicate the invisible and unrewarded work to get "things back 'on track' in the face of the unexpected." (Star and Strauss 1999, p. 10) A typical example is the daily work of nurses in hospitals which is fundamental to the seamless flow of events but often neglected by system designers. Articulation work is then intended as a design strategy to specify how systems might facilitate a reduction in the complexity of cooperative work arrangements that are individually conducted and distributed yet interdependent (Schmidt and Bannon 1992).

The invitation to move from "artefacts to infrastructures" resonates methodologically with the concept of *infrastructural inversion*, introduced to describe the continuous strategies of both actors and researchers to fore-front the daily non-heroic work required to maintain and upgrade infrastructures (Bowker 1994; Bowker and Star 1999; Edwards 2010). The attention is shifted from the users/artifacts relationships, to the work to sustain, upgrade, and maintain the infrastructural relationships. Jensen and Winthereik (2013) offer a similar definition for practical ontology. Following the actor-network tradition of having the study of relationships as a unit of analysis, practical ontology is at the same time a description of the daily work of people, technologies, and organizations, and of the strategies of researchers to elicit that work. While I maintain the actor-network theory influence and perspective, I will only speak of infrastructural inversion in the remainder of this thesis.

Kaltenbrunner (2014, p. 5) proposes looking at infrastructural inversion as a specific form of articulation work where

> "no instance of inversion (…) uncovers infrastructure as it really is, but always constitutes a situated effort to reconstruct infrastructure. (…) Collapsing inversion and articulation work emphasizes that the reflexivity of actors in everyday work settings is not essentially different from the reflexivity of inverting analysts."

The strong similarity between the concepts of articulation work and infrastructural inversion is important to capitalize on the research conducted in CSCW to scrutinize the "work to make a network work." (Bowers 1994) Inversion can constitute a generative resource for actors to innovate infrastructure by reinterpreting the potentiality of infrastructures and creating the conditions to embed new tools in particular ways (Kaltenbrunner 2014). Unlike Kaltenbrunner, I prefer to recognize infrastructural inversion as a generalization of articulation work (Paper 4) to mirror the broadening of the analytical lens from "artefacts to infrastructures." Regardless of this difference, both notions imply "going backstage" (Goffman 1959), a "gestalt switch" to look into the arrangements that tend to fade in the background (Bowker and Star 1999) and "shift the emphasis from changes in infrastructural components to changes in infrastructural relations." (Bowker et al. 2010, p. 99)

The following is a means to look at infrastructural inversions as a generalization of articulation work. In a nutshell, there are two ways to think of articulation work. The first is to conceive of it as the almost immediate work to make technology work. In general it can be considered stable, and routines can be defined. A second type of articulation work is that which unfolds over time and encompasses the broader efforts to create a working infrastructure that is far from being stable and is still in the making. While the first category of articulation work has proven powerful for describing artifact-based collaboration and coordination activities, infrastructural inversion can be used to address the second category due to its intrinsically unbounded temporal extension.

Infrastructural inversion is by nature a generic notion that requires operationalization. I would like to identify here a few of the features of inversion proposed in the literature upon which this thesis hinges.

First, infrastructural inversion is a concept that primarily underlines the idea that organizational work is fundamental to scientific work (Bowker 1994). Bowker describes the work of the oil service company Schlumberger in the 1920s-1930s in creating methodologies and a whole science of testing and measuring oil fields. Through this approach, Schlumberger managed to become today's leading company in its sector and its methods are still basic to petroleum science. The seemingly value-free scientific measurements were seamlessly embedded into the natural and social context. Edwards (2010) also makes use of infrastructural inversion to describe the evolution of climate science into what it is today. He describes how climate scientists in the 1970s had to make global sense of inconsistent and poorly standardized datasets collected from surface stations by reconstructing the history of the atmosphere, digitizing, and interpolating data in many ways. In parallel, inversion also indicates the unofficial activity of "citizen science" websites to verify the results of official climate science.

In a sense, infrastructural inversion clarifies how the object of research of an infrastructure emerges as a scientific problem. As reviewed in Section 2.1, environmental risk is epistemic: it evolves as our knowledge of it evolves (cf. Knorr-Cetina 2009). Ribes and Polk (2015) ask how scientific infrastructure can sustain itself while its epistemic object of research (HIV in this case) changes over time. Ribes and Polk conclude that studies of infrastructure, before characterizing the flexibility of infrastructures, must be specific about the nature of the change occurring. The underlying idea is that change occurs within the relationship between infrastructures and their object of research. After all, nature is a continuous process of feedback between theory and observations, where the construction of new instruments changes what we see, and how we see it (Latour 2004). Within CSCW, Ribes (2014b) examines how a set of resources and services become entangled with the work, techniques, and technologies that ensure the survival of the infrastructure. This approach echoes Schmidt and Bannon's (1992) invitation to CSCW to be concerned with the support requirements of cooperative work arrangements. A relevant aspect of Ribes' (2014b) contribution is that among the resources and services offered by infrastructures, are not only those which have been more center-stage in the CSCW literature, such as collaborative tools and datasets. Again we are reminded of the centrality for knowledge construction of the materiality of instruments and natural elements such as specimens (Bowker and Star 1999).

A second cardinal element of infrastructural inversion is that it unravels the way that infrastructure embodies and maintains controversies on several grounds by making hidden infrastructural references visible (cf. Star and Strauss 1999). Again in the words of Edwards (2010, p. 22):

> "Inverting the weather and climate knowledge infrastructures and tracing their history reveal profound relationships, interdependences, and conflicts among their scientific, technological, social, and political elements."

Indeed, infrastructural inversion does not simply reveal the social construction of facts (cf. Pinch and Bijker 1984), but their intrinsically infrastructural nature (Edwards 2010, p. 22):

> "The difference between controversial claims and settled knowledge often lies in the degree to which the production process is submerged. Thus, *an established fact is one supported by an infrastructure*."

Analyzing how the infrastructure is built and questioned therefore reveals how 'facts' are constructed as a public problem.

2.3.2 Integration by infrastructuring

Wearing the glasses of infrastructural inversion, I am now better positioned to address the integration of new capabilities into infrastructures by taking advantage of the latter's instability, uncertainty, and value-ladenness to address temporal, spatial, scientific, and political tensions. Star and Bowker (2002) proposed sensitizing researchers to these features by using infrastructure as a transitive verb. The term *infrastructuring* was then adopted in STS, CSCW, and IS to study infrastructures-in-the-making (Bossen and Markussen 2010; Pipek and Wulf 2009). In IS, Pipek and Wulf (2009) use the term to include all activities that contribute to the successful establishment of work-oriented infrastructures and "to avoid confusion with classic notions of design as design-before-use performed by professional designers." (ibid, p. 450) Pipek and Wulf's point underlines that the classic notions of 'design' and 'development' as defined and bounded tasks do not apply well to the features of infrastructures I reviewed above (see also Monteiro et al. 2013). Moreover, infrastructure design and development always also consist of the fundamental but often hidden and forgotten work of repair and maintenance (Graham and Thrift 2007). As reviewed by Karasti (2014), infrastructuring has been proposed as a more inclusive approach where "the boundaries between use, design, implementation, modification, maintenance, and redesign are blurred." (p. 143) Infrastructuring is a more appropriate metaphor because it focuses attention on the ongoing and reflexive work of designers and users to maintain the infrastructure by keeping it flexible to meet uncertainties and future problems. The adjective 'reflexive' is not used arbitrarily here, but refers to reflexivity as a characteristic of work infrastructures, specifically because designers and users belong under the same infrastructure and all improvements to the infrastructure are developed within the same infrastructure (Pipek and Wulf 2009) – an aspect that ultimately blurs the sharp distinction between 'user' and 'designer'. This definition of reflexivity reminds us of that characterizing environmental risk (Beck 1992; Latour 2003): as introduced in Section 2.1, it is the reverberation of the consequences of human knowledge on society that generates risks. This similitude therefore makes infrastructuring a suitable notion through which to address the integration of infrastructures for environmental risk management.

It is important to note that the idea of infrastructuring resonates with Orlikowski and Scott's (2008) understanding of technology development, implementation, and early use, not as special cases, but rather as sociomaterial enactments of boundaries and relations within practice (see also Section 2.2.2). There is therefore a performative view at the center of the notion of infrastructuring, because, in its reflexivity, it constitutes reality in practice. The infrastructuring perspective also shares commonalities with the notion of cultivation, namely strategies – including bootstrapping – to ensure the self-reinforcing of the installed base to enable its growth (Hanseth 1996). By not making assumptions about who is doing what and how, the concept of infrastructuring is better equipped to characterize highly uncertain innovation processes, as is the case for NorthOil. In CSCW Bossen and Markussen (2010) analyze infrastructuring in health care and describe how practices and artifacts become part of long-reach technological and social networks which extend the scope of coordinative practices. In this way, dependency on external unforeseen events is increased, inscribing external actors' concerns into artifacts in use by a professional group. Infrastructuring has also emerged in a stream of literature studying infrastructures for eScience: the development of artifacts, shared vocabularies, and work practices for large-scale and long-term coordination and collaboration among scientific communities (Baker and Millerand 2010; Karasti et al. 2006). Here, infrastructuring is meant as the work to preserve datasets and develop new capabilities to enhance their capture and use, especially when future needs cannot be foreseen, often by balancing large-scale demands with local-scale developments.

In sum, infrastructuring overtakes clear-cut distinctions that do not apply well to infrastructure, such as that between design and development and among users, designers, and developers. It does so by underlining the *continuous* and *performative* nature of integration. It is a powerful notion with which to address the time dimension. In other words, infrastructuring is a way to build infrastructure by placing bets on the future in the face of uncertainty. As a consequence, it also helps to overcome spatial limitation, because it explains the continuous integration work of drawing new connections with new modules, systems, practices, and stakeholders/users. Finally, it is a pragmatic strategy: by allowing the roles of user and designer to overlap, it shows that infrastructure evolution can take place through ad-hoc, possibly short-lived articulation efforts.

In Paper 4 we propose to operationalize the time-dependent dynamics of infrastructuring through two concepts: bootstrapping and enactment. We use bootstrapping to describe the heuristic and emerging strategies to address the early stages of infrastructure evolution (Bowker 1994). We nonetheless recognize that matters of bootstrapping resurface during later critical phases of infrastructuring. Infrastructures are indeed recursive: the more gaps are filled, the more gaps are perceived (Jensen and Winthereik 2013). Enactment is a concept we borrow from Mol (2002) to characterize later stages of infrastructure evolution (or when the integration concerns become more apparent). Enactment addresses the flexible work of integration that does not rely on unity and a lack of controversy as pre-conditions and acknowledges that several levels of materiality shape the integration process.

2.3.3 Summary

In summary of the two key concepts introduced in the previous section:

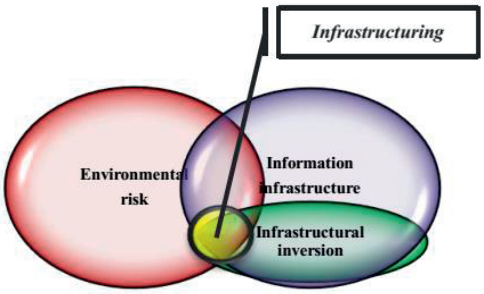
- *Infrastructural inversion*. Infrastructural inversion is an analytic lens to shift the attention of researchers and actors from the relationships between end users and artifacts to the often hidden infrastructural relationships that sustain them. It also serves to address the different temporal scales particularly involved in the early dynamics of infrastructures-in-the-making. Inversion reveals how organizational work is fundamental to scientific work and how infrastructure is able to embody and maintain controversies on several levels. In this way, it demonstrates how the construction of ‘facts’ is infrastructural in nature.
- *Infrastructuring*. All the concepts introduced in this chapter combine to shape the notion of infrastructuring. Infrastructuring deals with the evolving and uncertain nature of integration in infrastructures. At a conceptual and practical level, it helps to overcome situated notions of design and development. It focuses attention on the performative and reflexive work of designers and users to sustain and maintain infrastructure by keeping it flexible in order to meet uncertainties and future problems. In other words, infrastructuring is a way to build infrastructure by placing bets in the future on the face of uncertainty.

2.4 Infrastructuring for environmental risk management

I propose discussing the early stages of the evolution of an information infrastructure for environmental risk management on the theoretical level as a matter of infrastructure integration. Specifically, I adopt *infrastructuring* to describe a *reflexive strategy of integration that focuses on the dynamic evolution of infrastructural relations.* Infrastructuring recognizes that the space and time of infrastructure is emergent and fluid, and always enacted in practice.

In particular, I propose infrastructuring as the intersection between the two cardinal themes of this thesis – environmental risk and information infrastructure – and the strategic approach of infrastructural inversion (Figure 4). *By placing my theoretical framework at the intersections of these themes, I want to underline that the phenomenon (environmental risk for one) and infrastructures are always co-constructed.* It is through the infrastructuring mechanisms that environmental risk is enacted and perceived as a problem. In turn, the perception of risk has consequences on infrastructuring mechanisms.

My perspective is grounded in the recognition that environmental risk is an epistemic problem: it evolves as our knowledge of it and our instrumentation to measure and represent it evolves (Bowker 2000; Ribes 2014b). In other words, to emerge as a 'fact', environmental risk needs the support of an infrastructure (Edwards 2010). The presentation of information regarding environmental issues equally has a rational and a social dimension (Malhotra et al. 2013). As a consequence, rather than 'risk' as a fixed object, what I refer to is the perceived nature of risk in the eyes of heterogeneous stakeholders (Douglas 1992).



I synthetize the theoretical framework of this thesis by selecting the following key characteristics:

- *Information infrastructures for environmental risk management*. Complex problems such as environmental sustainability in general and risk management in particular might be better addressed through the lens of infrastructures, which is more suitable for answering questions of scale, such as expanding the size of solutions for sustainability and at the same time, making global solutions locally useful (Silvast et al. 2013; cf. Edwards 2010). The fruitfulness of the infrastructure lens for environmental sustainability is acknowledged by the contributions within CSCW and STS on eScience that discuss the development and maintenance of infrastructures to store and share environmental data across diverse scientific communities.

- *Environmental risk management as equifinal integration*. Environmental risk management is an uncertain, long-term, cross-disciplinary, and scientific practice where tensions arise among various experts, technologies, and between the long-term and short-term value of data and of technology development (Borgman et al. 2012; Karasti et al. 2010). I propose to study it as an ongoing effort of equifinal integration: by maintaining contrasting spatial, temporal, or political perspectives but still preserving an acceptable final state by means of short-lived and ad-hoc forms of articulation.

- *The material nesting of environmental risk definition.* When looking at infrastructures for risk management, materiality has socio-political implications: “the complexities of natural and technological systems and the consequent difficulties in knowing and governing the behavior of materials can provoke or contribute to the mutation of [public] controversies.” (Barry 2013, p. 13) Acknowledging that material reality is performative means recognizing the relationality of infrastructure: materials “never exist as isolated entities, but are themselves evolving entities that form part of a constellation of dynamic relations with other entities.” (ibid; cf. Pickering 1992) Environmental risk is therefore continuously constituted through a process of material nesting where its boundaries (what is risk and what is not risk, what is inside the risk assessment and what is outside) are drawn temporarily through practice to give situated determinacy to a phenomenon (e.g., the discharge of drill cuttings onto corals) (Paper 5; cf. Orlikowski and Scott 2008).

3 Case

This chapter presents the context of the events and possibilities that are paving the way for the integration of real-time environmental monitoring solutions with oil and gas technical systems and work practices. Industry-driven environmental monitoring initiatives build upon the experiences and expertise of scientific disciplines such as marine biology, environmental chemistry, physics, zoology, and oceanography. In recent years web portals have, for instance, been developed by scientists to share sensor-based oceanographic datasets and maps. A relevant example is the Alaska Ocean Observing System[3], where sensor feeds, satellite observations, and GIS data sets are combined to map the physical characteristics of Alaska and the nearby oceans. The Mareano program by the Norwegian Institute for Marine Research[4] publishes detailed maps of the topography, geology, sediment composition, biodiversity (e.g., fish migration, coral reefs), and reported pollution on the Norwegian seabed areas. Finally, the SAM-X web portal[5] makes available datasets from the Institute for Marine Research and the Fishery Directorate to facilitate the planning of seismic activities by the oil and gas industry.

In the remainder of this chapter I first provide an overview of the relationships between the oil and gas sector and environmental concerns. I later zoom in on a specific context, Norway. Finally, I discuss the motivations and initiatives of one the largest Norwegian oil and gas company (NorthOil, a pseudonym) to establish an infrastructure for integrated real-time environmental monitoring during its offshore operations.

3.1 Environmental monitoring and oil and gas operations

In recent years oil and gas offshore operations have developed at a steady pace. Technological innovation today makes it possible to search for oil or natural gas in increasingly deeper waters (e.g. in the Gulf of Mexico and offshore Brazil) and to extract heavy oil from reservoirs at low pressure.

The environmental risks connected with such advances are *potentially* huge. Assessing the environmental risk associated with oil and gas operations is however subject to several *uncertainties* at the scientific, political, and economic level. The core of my case revolves around the uncertain and potential nature of environmental risk.

Uncertainty affects risk assessment firstly on the scientific level. Today's decision making processes are mostly fueled by worst-case scenarios (e.g., a big oil spill). The

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[3] http://www.aoos.org
[4] http://www.mareano.no
[5] http://www.epim.no/sam-x

scope of the harms caused by routine operations (i.e., when everything seems to go according to plans) to the environment and the adjoined economic sectors is however difficult to establish (Blanchard et al. 2014; Hauge et al. 2014). Nevertheless, as scholars vividly illustrated, risk assessment often reveals social and political interests that are inscribed in the decisions of what should be defined as at risk and to what extent (Jasanoff 1999). The excerpt of an interview I held with an environmental chemist (NorthOil) vividly exemplifies how environmental monitoring is sometimes more dependent on the political and popular background of each country or region than on a solid scientific basis:

> *Environmental chemist: "[I]nternational companies [have] to face sometimes extremely different regulations even though the environment might be quite comparable. So depending on where you are and which jurisdiction [applies], the regulation can be dramatically different. And not only the regulations, but also which environmental factors or compartment or even what species is important. If you pass a border suddenly a focus is completely changed – even though the environment is exactly the same on both sides of the border, so that can be quite interesting."*
>
> *Me: "The border between Norway and Russia, could it be an example?"*
>
> *E. c.: "Yeah, that could be an example. We have done some work and I have been involved for several years in Canada and it is fascinating the focus that not only the regulators but the public as such, as a whole, has on certain species. And it is not always based… or so to speak it is never based on a deep understanding of the ecology of the area, it is more like "Yes, the reindeer is important!" and ok there is a lot of focus on the reindeer but that is only one of the 20 species of large mammals in the area!"*
>
> *Me: Yeah that is an interesting point... why some points are foregrounded, what are the actual reasons for that?"*
>
> *E. c.: "Exactly. And it's a good example too because it leads me to state how important basic research is for doing the work that we are doing. In this area, in Western Canada, in the province called Alberta, there has been a concern for many years that the reindeer population, the caribou which is the local name for that species, the number has been declining so the regulators were looking for ways to increase the population and they decided that by killing five thousand wolves in this area per year, they would boost the population of caribou. Which initially seemed like a good idea, right. But then NorthOil came and for several years we have done baseline surveys of caribou based on the scat – or the poo of the animal that we collected during the winter [we laugh] – it's sort of an interesting project and we did DNA analysis of these excrements to identify which animal it was. Based on this we could do several artificial mark recapture study, which is a very typical way of estimating the size of a population. So first you could say that actually in this area the population is much larger than you have thought. So there might be not such a large reason for being worried in the first place. And second we can say that by analyzing the wolves' droppings we could say that the wolf is actually not eating that much reindeer. It's actually eating much more deer. It actually doesn't eat caribou at all. So if you want you can go out and shoot five thousands wolves per year, that is totally fine, but you are not going to save the caribou by doing that. You're probably going to get more deer."*
>
> *Me: "And then the ecological balance…"*
>
> *E. c.: "The balance between the deer and the reindeer would probably shift in favor of the deer. So that would actually put a much larger stress on the caribou rather than helping it."*

Oil and gas well operations consist of a number of interconnected activities that span many decades: exploring for new subsurface reservoirs (years); planning a new field or a new well (few years); drilling a well for exploration or extraction purposes (few days); producing oil or natural gas (potentially decades); dismissing and demobilizing the exhausted well (few years).

One of the most delicate activities is drilling a new well, especially when the top-hole section is perforated. A notorious example of a drilling operation gone wrong is the Macondo blowout in the Gulf of Mexico, where the oil and gas company operating the reservoir and its contractors failed to control the huge pressure difference between the reservoir and the atmosphere by, among other things, using defective cement on the well and failing to operate the valve meant to prevent blowouts (the so-called blowout preventer) (OSC 2011). The point I want to emphasize here is the assessment of President Obama's commission which called for a reconsideration of the socio-technical system to which the oil and gas industry belongs (ibid, p. 294). This call is interesting in that it avoids technological determinism and frames the problem of the environmental impact of operations as a holistic one. What follows is an acknowledgement that legal and moral responsibilities should be reconfigured to accommodate the evolving relationship between human technology and its context, where the natural environment is a key stakeholder.

There are international organizations in charge of setting regulations, defining the threshold values to assess environmental pollution, and defining the list of threatened marine species. One such organization is the Oslo-Paris (OSPAR) commission, founded in 1992 as a referee for the countries in the North Atlantic region[6]. Balancing the large (national or international) scope of normative activities in such organizations and the variety of local ecosystems, is nevertheless difficult. Environmental monitoring programs are often set at a regional level to look at single aspects of ecological health, but they often fail to turn into comprehensive frameworks for ecosystem management (Knol 2013), even when attempts to develop integrated approaches in specific areas are underway (NME 2011).

This point is relevant because recent studies estimate that approximately 25-30% of the world's undiscovered resources are buried in the Arctic areas of the world (the High North) (Bird et al. 2008). Not only is the Arctic region rich in environmentally sensitive flora and fauna, but it is also characterized by harsh and unpredictable weather conditions. Another international oil and gas company was denied permission to operate in offshore North Alaska in 2012 (DOI 2013). The US Department of the Interior noted the company's deficiencies in managing contractors and stakeholders. In a mindset that echoes the assessment report of the Macondo accident – but in a case where an accident has not happened yet – the stakeholders were also identified as the local onshore communities that would be affected in the case of *potential* harm to the environment. In

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[6] http://www.ospar.org

2015 the company issued a new request for drilling in the Arctic investing one billion dollars in the project (Macalister and Carrington 2015); see also Figure 2.

The bottom line of this introductory section is that the relationship between oil and gas activities and the environment unfolds differently in different contexts, depending on the entanglement of the technology available, the political and social regime of a country, and the natural environment in which operations are conducted (Barry 2013).

On this premise, I am interested in studying the work to build and sustain infrastructures for offshore environmental monitoring and to integrate them with the routine practices of oil and gas operations.

To do so, I will now narrow my focus to one very specific setting: Norway.

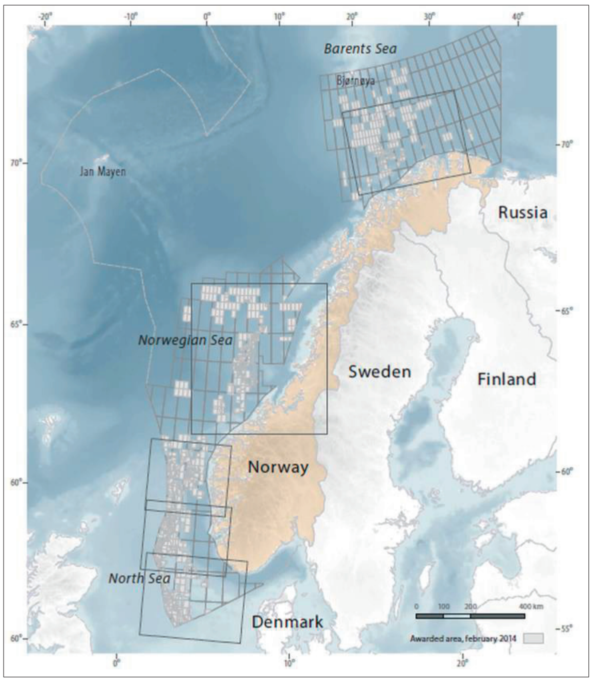

Figure 5. Areas on the Norwegian continental shelf (Source: The Norwegian Petroleum Directorate).

3.2 “Norway is a special case”

> *“It is interesting now to see that many other countries are following closely how [subsea environmental monitoring] has been done in Norway and also many developing oil and gas nations want to deploy the same system that we have [in Norway]. In many countries where oil and gas activities have been going on for several*

> *decades already they have chosen a completely different approach, where it is more of a fight than a collaboration between the state and the companies. And this is interesting to see when we move abroad and we come with our culture and our mindset to for example areas like the Gulf of Mexico." (Environmental chemist, interview, May 2013)*

The Obama commission which investigated the Macondo accident proposed Norway as a model for development of the American oil and gas business, so as to avoid creating the conditions that caused the blowout (OSC 2011).

Why Norway?

The abundancy of oil and gas resources in the so-called petro-states has often generated little wealth for local inhabitants and the exploitation of local resources by international oil and gas corporations. Norway is one country that, although capitalistic, managed to turn the income created by the oil and gas business into strong social welfare programs (Behrends et al. 2013). As the environmental chemist quoted above implies, Norway is indeed a special case[7]: it is characterized by a historical tradition of collaboration between the oil and gas operators and the authorities that is more of an exception than the rule elsewhere. As an example, one of my informants – an environmental advisor employed by a Norwegian oil and gas company – is also a member of the aforementioned North Atlantic OSPAR commission. She told me that other OSPAR members from other countries were surprised to hear that Norway would send a representative from an oil and gas company to an environmental regulatory organization. To her, this dual role was not a paradox, however, as close dialogue and exchange with the environmental authorities is common practice in Norway.

If we look at the political agenda of the Norwegian governments, the picture becomes, needless to say, more complex, and it follows the gradual expansion of oil and gas activities in Norwegian waters.

The Norwegian Continental Shelf (NCS) is of significant size, constituting approximately one third of the European continental shelf, and encompassing a narrow area in the longitudinal direction comprising onshore Norway and its portions of the North Sea, the Norwegian Sea, and the Barents Sea in the High North (Figure 5). After political and social negotiations, the Norwegian government has become the only landowner of the NCS since 1963. The territory is divided into quadrants of 1 degree by 1 degree, which are assigned through periodic licensing rounds by the Ministry of Petroleum and Energy to a consortium of operators for exploration and – if resources are found – production (Hasle et al. 2009). There have long been concerns about the assignment of blocks into gradually more environmentally sensible offshore areas

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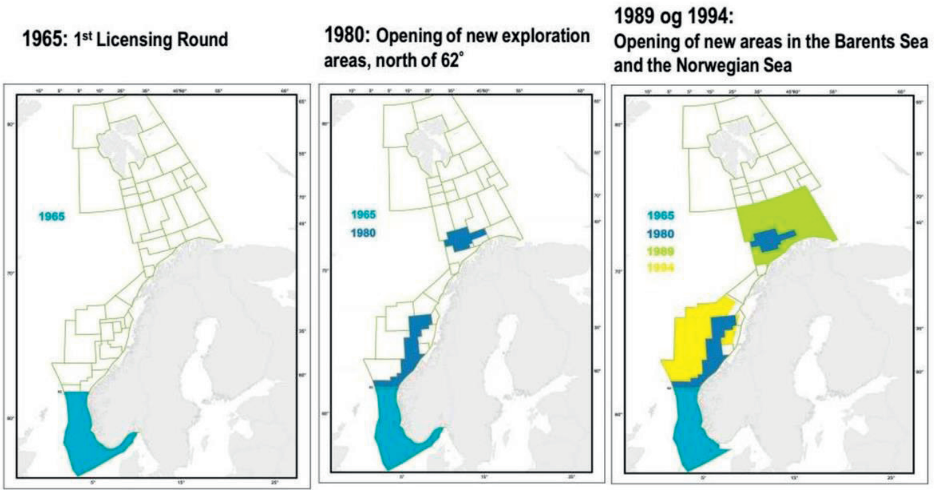
[7] I thank Robin Williams for highlighting this aspect.

(Figure 6). For example, between 1965 and 1980 oil and gas companies were only allowed to explore for oil and natural gas and to operate below the 62° degree of latitude – which is taken as the northern limit of the North Sea. This choice was meant to guarantee a moderate pace in the development of a national industry ("Norway's oil history in 5 minutes" 2013). Most likely, it was also dictated by the difficulty of operating in the harsh northern weather conditions. In 1980 the northern boundary to operations was moved up, and the first production licenses were awarded in the Norwegian Sea and the southern Barents Sea. In 1989 and in the 1990s new blocks were assigned to operators in the northern part of the Norwegian Sea and into the Barents Sea.


1965: 1st Licensing Round

1980: Opening of new exploration areas, north of 62°

1989 og 1994: Opening of new areas in the Barents Sea and the Norwegian Sea

Figure 6. Main steps of the expansions of oil and gas activities on the NCS. Source: The Norwegian Petroleum Directorate.

Environmental activists and organizations such as Bellona[8] protested against this northwards move, arguing that oil and gas operators are not able to preserve the sensitive environment in the Arctic region (Knol 2011). Norwegian governments have issued several management plans in the last two decades to guide the preservation of the environmental value of sensitive areas (NME 2006, 2011). Importantly, such plans are targeted at all industrial activities on the NCS, and therefore not only oil and gas activities but also fisheries, tourism, and marine transport. The main areas currently still forbidden to oil and gas activities are the seas off north Norway, along the Lofoten

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[8] http://bellona.org

Islands, Senja, and the Vesterålen region, identified by the Ministry of the Environment as particularly vulnerable after a knowledge gathering process (NME 2011).

In general, environmental policy is one of the top priorities of Norwegian governments, and became visible during the previous laborist government, which pledged to make Norway neutral to carbon emissions by 2030. Promises to finance reforestation in developing countries were also made in connection to the Kyoto Protocol. As underlined by some international media, however, this approach is at apparent odds with the fact that the Norwegian state finances the country's petroleum sector, whose revenues are fed into the world's biggest sovereign Pension Fund[9]. I will not in this thesis provide an insightful analysis of Norwegian politics, but I emphasize that this seeming paradox puts pressure on the Norwegian regulators and the oil and gas companies to take strong initiatives towards more environmental sustainable activities. During the campaign that preceded the latest elections (2013) the debate about whether to reduce or stop oil and gas activities in Norway made many newspapers headlines. In particular, the possibility of opening the Lofoten-Vesterålen-Senja area to oil and gas operations caused harsh debates. These debates increased as a proposal was issued in 2015 to move the border of the permanent ice barrier as a consequence of the Arctic ice melting, before a new licensing round to assign blocks to operators (Koranyi 2015).

The case studied in this thesis unfolds against the backdrop of these heated debates.

If we think of the NCS as a stage, I now briefly introduce two of its main actors: the natural submarine environment and the oil and gas business. Since all Norwegian oil and gas resources are extracted offshore, reference is always to offshore oil or natural gas wells. 'Natural environment' refers to the marine ecosystem.

3.2.1 The NCS and its natural environment

Given the length of the NCS, the variety of its submarine life is remarkable. As marine biologists have found, for least 9000 years it has been home to the world's largest population of a species of cold-water coral, *Lophelia pertusa* (Fosså et al. 2002).

The NCS also has its narrowest point off the Lofoten-Vesterålen-Senja region, an area I dub 'Venus' for simplicity. On the one hand, seismic explorations in the past have shown that Venus hides promising oil and gas resources. On the other hand, the area has a unique landscape, is a key spawning and nursery ground for commercially relevant fish species such as cod and herring, and hosts the world's largest known deep-sea coral reef (Hauge et al. 2014). The opening of Venus to oil and gas operations is dependent

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[9] The Government Pension Fund of Norway (called 'The Oil Fund' until 2006) is a fund where the surplus income from oil and gas activities is deposited. Its current market value is almost 7 thousands billion NOK (refer to http://www.nbim.no/en/; accessed April 24th, 2015).

on the protection of this sensitive environment. Other marine species inhabit the NCS, including marine mammals, however, as some of my informants have indicated, they have not been the main focus of the law or environmental monitoring activities on the NCS.

Fish and corals are particularly interesting because, upon close scrutiny, they carry signs of the complex relationship between the oil and gas sector and the fisheries, the two main industries of the country. On the one hand, mass media tend to focus on the economic damage to the fishing activities that is caused by oil and gas operations. The fisheries of north Norway, for instance, claim that sending seismic signals from the sea surface downwards towards the Earth crust to search for oil and gas scares the fish away (Vegstein 2014). It has however also been demonstrated that approximately 50% of Norwegian coral reefs have been damaged by bottom trawling fishing activity (Fosså et al. 2002). On the other hand, a portion of the oil and gas revenues is used to support the fisheries, and the Venus area remains closed to oil and gas activities to prevent any harm to the reproduction of fish species that are commercially relevant to the fishermen.

3.2.2 The Norwegian oil and gas sector and NorthOil

The discovery of oil in the NCS is fairly recent, dating back to 1969, when an American company found the Ekofisk field – still active today. Since then, through a gradual learning process via foreign expertise, a national oil and gas sector comprising operators, technology vendors, and consultants has developed to become the leading industrial sector in the country: it accounts for more than 20% of the GPD and almost 50% of total exports (MPE 2014). Even though the production peak seems to be past (although the newly discovered Johan Sverdrup field shows that there are still undiscovered subsurface reservoirs in the North Sea), today it is estimated that 30% of the undiscovered Norwegian oil and gas resources are expected to be in the Barents Sea (Hasle et al. 2009).

To counterbalance the power of the industrial associations related to the oil and gas domain (Norwegian Petroleum Directorate, NPD[10]; Norwegian Oil and Gas[11]), agencies have been established to gather knowledge and set regulations to prevent damage to the marine ecosystem (e.g., the Norwegian Environment Agency[12] and the Petroleum Safety Authority[13] (PSA)).

The regulatory framework for offshore activities has evolved over the last three decades. Back in the 1980s, drilling activity relied on polluting oil-based fluids that

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[10] http://www.npd.no
[11] http://www.norskoljeoggass.no
[12] http://www.miljodirektoratet.no
[13] http://www.psa.no

were later diffused in the water. In the 1990s however, oil and gas operators began instead to adopt water-based drilling fluids, also pushed by stricter discharge regulations for example in the North Sea and the Norwegian Sea. After operations were opened to areas above latitude 62° north in 1980, a much stricter constraint prevents any type of physical discharge outside northern Norway and in the Barents Sea (NME 2011).

Based on my data I identified a list of key points in the trajectory of the Norwegian oil and gas business and environmental concerns (see Table 2). To discuss the development of subsea environmental monitoring programs in the Norwegian context, two points in its timeline are particularly relevant. These events also indicate the starting date of my empirical case. The choice is motivated by the individuation of two pivotal initiatives which later became crucial enablers of integrated monitoring programs at the normative (point 1), financial (point 2), and technical level (point 2):

1) 2002 (approximately): The Norwegian PSA publishes the Human, Safety, and Environment (HSE) regulations, with a focus on the continuous monitoring of the natural environment.
2) 2004: The Norwegian Oil and Gas Association formally promotes a strategy based on 'Integrated Operations' and enrolls the oil and gas companies operating in Norway. What follows is the gradual installation of fiber-optic cables and the adoption of collaborative and videoconference information systems.

The PSA has begun to set the focus on a more continuous and integrated approach to the monitoring of the natural environment, as opposed to sporadic risk assessment rounds. The most recent formulation states that "*Sufficient information shall be obtained to ensure that all pollution caused by own activities is detected, mapped, assessed and notified, so that necessary measures can be implemented.*"[14] A continuous and integrated approach to monitoring (Point 1) would not be possible without the development of technology and work processes boosted by what the Norwegian Oil and Gas Association calls Integrated Operations (Point 2) (Henderson et al. 2013). Integrated Operations were motivated by the aftermath of the Enron scandal and in the wake of the prediction of a decrease in the worlds' oil and gas production. They emerged as a solution to facilitate accountability, operate short-lived fields, and communicate more efficiently between offshore installations and onshore control centers. Fiber-optic cables are being installed on the NCS to provide offshore sites with faster data transfer and connectivity to the onshore control centers and to enhance unmanned operations (Figure 7). Moreover, the gradual installation of cross-organizational file sharing systems, cross-disciplinary work processes, and videoconferencing tools allows faster communication between dispersed personnel (see also Paper 4).

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[14] http://www.psa.no/framework-hse/category403.html#p48. Accessed March 16th, 2015.

Figure 7. Subsea installations that are equipped with multiple sensors (Source: Digital Oil project description, www.doil.no).

NorthOil

NorthOil was established in the early 1970s with the state as the only stakeholder. Today NorthOil is only partly owned by the Norwegian state and is listed on the New York Stock Exchange. It currently employs around 23,000 people, with activities in 36 countries on 4 continents. Historically organized around the geographical site of the oil and gas field to take advantage of situated extensive and practical experience, NorthOil has evolved into a matrix organization where different business units are responsible for specific functions. A great effort in connection with Integrated Operations has been made to develop work processes that regulate the activities of different units in a standardized manner, regardless of the geographical location of operations. Currently more than 30,000 official work processes at variable levels of detail are in use in NorthOil to connect the work of, for example, geologists, engineers, and data management experts.

In sum, NorthOil is governed both by internal corporate regulations and by external requirements including Norwegian laws; the laws of the countries where operations are taking place and where the company is listed in the stock exchange; and the Health, Safety, and Environment norms established by national and international bodies.

Table 2. Timeline of facts relevant to the relationship between environmental concerns and oil and gas activities. The dotted line indicates the starting point of the case considered in this thesis.

Year	General context	Norway	NorthOil	ICT
1969	Oil discovered in the North Sea			
1972			NorthOil established	

1980		Oil and gas operations allowed above latitude 62° north		
1982			Lophelia spotted in the Barents Sea	
1989		Opening of new areas in the Barents Sea		
1992	OSPAR commission begins			Collaborative ICT projects initiated at NorthOil (e.g. Lotus)
2002 (ca)		HSE regulations shared between Petroleum Safety Authority and Environment Agency		DREAM simulation software is available (Reed and Hetland, 2002)
2003	Lophelia considered as a threatened species by the OSPAR Convention			
2004	Official focus on Integrated Operations by Norwegian oil and gas Association			Installation of fiber-optic connections and shared collaborative software begins as part of Integrated Operations
2006		Integrated Management of the Marine Environment of the Barents Sea and the Sea Areas off the Lofoten Islands		
2007			- First joint projects to study the corals, e.g. with offshore cruises. - Development of Peter field is started	
2008	Estimation that 25-30% of oil and natural gas undiscovered resources lie in the Arctic region		First ocean observatory deployed in Venus. GlobalMapping begins	
2009		Integrated Management of the Marine Environment of the Norwegian Sea.	Environmental monitoring in Peter begins (autumn)	
2010	Macondo blowout in the gulf of Mexico (April)	Regulations on environmental monitoring for the petroleum industry on the NCS by Environment Agency	Ocean observatory deployed in Peter (May)	
2011	Agreement on sea borders delimitation and collaboration with Russia	First update of the Integrated Management Plan for the Marine Environment of the Barents Sea–Lofoten Area	- EnviroTime starts with Use Case 1 - Venus financed by production and development department internal project	

2012	Fieldwork begins (April)	QCB issues guideline for coral risk assessment to the Norwegian oil and gas Association	- Agreement with Russian state-owned energy company for Arctic explorations - GlobalMapping is closed	EnviroTime focus on developing a data model based on semantic technologies
2013			- EnviroTime Use Case 2 begins (November) - Decision to incorporate Venus data in EnviroTime Use Case 2 - Venus financed by EnviroTime	- Completion of fiber-optic cable to connect Venus Ocean Observatory (June) - Venus web portal online (September) - Presentation of portal to the fishermen (November)
2014	- Drop of oil price (December) - Fieldwork ends (December)		- Venus Ocean Observatory taken onshore for maintenance (June) and redeployment (October) - EnviroTime Use Case 3 starts (September) - Decision to focus more on Use Case 1	The Venus web portal is offline due to ocean observatory maintenance (June-October)

3.3 Towards an integrated real-time infrastructure for environmental monitoring in NorthOil

This section selectively overviews the constitution of NorthOil's current environmental monitoring capabilities. In the first part of the chapter (3.3.1), I present a general portrait of the underwater monitoring practices in the Norwegian context prior to the investments in real-time data transfer and visualization technologies. Such practices are still widely adopted. The second part of this chapter (from 3.3.2) presents NorthOil's projects, which are embedded units of analysis throughout my PhD project, even though not all of them are directly related to environmental monitoring. These projects constitute relevant steps in the trajectory towards an integrated and real-time approach environmental monitoring in NorthOil. The qualifier 'integrated' refers to the incorporation of environmental monitoring tasks and systems into the activities of the heterogeneous professionals operating an oil or natural gas installation. The change towards real-time data transfer technologies is happening on a broader scale in the oil and gas sector, in line with the principles of Integrated Operations. As one industry leader stated, "*[shifting to] real-time operations is the next revolution [in oil and gas].*" ("Energyworld" 2014) Change is happening as we speak, and its advantages and boundaries are still unclear. A vivid example is the adoption of wired drill pipes while drilling a new well, where online datasets are sent to operators through fiber-optic cables from a borehole. As one of my informants from NorthOil observed:

> "*[I]t takes time to mature. One thing is to just apply the technology, another thing is to take advantage of it. That's probably one of the reasons it's been a bit delayed in NorthOil (...) We need to have a strong business case for it.*"

Framed differently: real-time technologies are available, but the process of their integration with the installed base of oil and gas operations is happening now and has not yet stabilized.

Several other companies and institutions are involved in NorthOil's projects. In Table 3 is a summary of those relevant to this case study, and their roles.

Table 3. A list of the companies partnering NorthOil's projects considered in this case study. All names are anonymized for confidentiality except for the IMR which is an independent research institution.

QCB	Third-party risk assessment and certification body; development of risk assessment methodologies
O&GSolutions	Vendor and expert in both oil and gas and submarine equipment and sensing devices
ITCorp	Provider of business analytics; semantic data modeling; passive acoustics data analysis systems
MAS	Subsea sensor technology vendor; marine acoustics expertise
IMR	Norwegian Institute for Marine Research; experience and development of methodologies in various fields of marine biology and oceanography

3.3.1 Traditional environmental monitoring

Offshore environmental monitoring on the NCS has to date been asynchronous and driven by regulations. In general, environmental experts from third-party service companies must conduct offshore monitoring campaigns every third year. The common practice is to collect samples of the water to measure its pH, of the sediments on the seabed, and of the benthic flora and fauna around an installation. The approach used to monitor corals is to take pictures and videos of the reefs. Fish are a moving target and more difficult to monitor in the wild. One solution is to lower cages holding various fish species into the vicinity of the operational point and withdraw them later to measure their degree of exposure to pollution.

Samples, pictures, and measurements are later taken onshore and analyzed, with temporal gaps of 9-12 months. The parameters for collection vary depending on the availability of detailed guideline from authorities:

> *"The parameters to look at [are] variable. For some programs it's very good guidelines, and (...) it [hasn't] changed for many years because it has been discussed through experts and documented. Other times, for instance we can*

> *decide for ourselves, just that we use a methodology that answers the questions the government asks."*

Along with pressure and temperature, the most common parameters that survey companies analyze are the direction and speed of the water currents (to predict the dispersion of biomass or drilling discharges); turbidity (the instantaneous concentration of particles in the water column); sedimentation (the progressive accumulation of particles on the sea bed); visual inspection of given points. These datasets are often fed into general-purpose software that models the dispersion in water of the predicted discharges produced while drilling. One example is the DREAM software (Rye and Ditlevsen 2011) developed in the early 2000s and still widely adopted for environmental risk assessment during oil and gas operations (see also Table 2). As described in Paper 5, this type of software abstracts drilling discharges to generic particles and describes their movements through mathematical formulas. The assumptions inscribed in the algorithms are such that these modeling tools are seldom capable of accounting for the wide variability of drilling operations. Modelling software such as DREAM does not distinguish particles in terms of their size, and it cannot therefore be specific about particle spread, which depends on their granularity.

Overall, the side effect of the data collection procedures, and the long period employed to analyze the data, is that environmental datasets are stored across several data sources in different formats. Videos and pictures on hard disks are, for example, only available to those employees or service companies directly in charge of the surveys, and sensor readings might be stored in database tables and the spreadsheets in the hands of different engineers. As one NorthOil environmental advisor complained during a meeting: "*Saving the data is not a problem. But we have so much already that we should have used but is not accessible!*" Admittedly, this fragmentation in environmental monitoring approaches is not a specific problem for oil and gas companies. It is instead a feature of the discipline of marine biology in general, still characterized by poor standardization of the units of measure, a lack of shared best practices, and poorly coordinated data collection and analysis.

3.3.2 The first ocean observatories (2007-2013)

"So then we needed to do something to show... to find out whether these guys [i.e. the corals] are sensitive or not for discharges." (Environmental advisor, interview, July 2013)

The Venus Ocean Observatory

'The Venus Ocean Observatory' encompasses all the projects conducted by NorthOil in the waters of the Venus area with the goal of installing a subsea sensor network to track oceanographic parameters. I identified these projects as significant because, as mentioned before, operations have not so far been allowed in Venus.

The first attempts to deploy a sensor network began, according to my informants, around 2007 as part of externally funded projects (e.g., by the EU) in collaboration with research institutions, technology vendors, and with NorthOil as the only energy company involved. The most important project partners were the IMR and a marine technology vendor (MAS).

Initially several technical breakdowns and malfunctions occurred, due for example to the strong winds and currents in the region. After a first phase of trial and error, the Venus project reached a turning point in 2011 when its business relevance was recognized by the strategic Arctic initiative in NorthOil's production and development department. The leaders of the Arctic initiative decided to finance the installation of a permanent observatory and of a fiber-optic cable to connect it to an onshore data center (actually a small wooden cabin) on the coast of north Norway. The installation of the fiber-optic cable was completed in 2013 – again after some technical accidents – and proved to be a good occasion for NorthOil to network with the local communities. The company decided to finance the installation of a fiber-optic Internet connection for the inhabitants of the village where the onshore data center was located.

This represented a key moment in the history of environmental monitoring: environmental data was now sent to shore in real time from a fixed monitoring station managed by an oil and gas company. Environmental monitoring was not yet integrated, but it was definitely in real time. Venus was also NorthOil's first and still functional fixed environmental observatory. As I will show later, in 2013 it became part of the corporate agenda.

The possibility of opening the Venus area to operations is a political 'hot topic' where NorthOil identified the business relevance of obtaining an overview of the environmental behavior in the area, in case of future permission to operate in the area. When asked about his experience with the Venus observatory, one NorthOil environmental advisor comments:

> "*The boring – in brackets! – thing with this is that there are no activities, there are no discharges. So this is natural. (...) No… for most of the marine researchers it's not boring at all. [But] we need to get some real stuff and some real discharges into this equation. But that has to be done in other areas*."

Triggered by this comment, I asked him whether the company was really using the Venus observatory to plan operations in the area. He admitted that NorthOil's initiative is dependent on the agenda of the different political parties. This interview was in fact held a couple of months before the most recent elections in Norway (2013) and gives a good overview of the political complexity behind the Venus project:

> "*[T]here is of course one reason why we are doing this: it is to gather background data for potential future operations. But this depends on a lot of things. It's very much dependent on the elections in Norway. (...) Because the situation is that in the government [Labor party] there is a clear majority for opening this area or at least to go for an impact assessment in the area for the potential opening (...) but then the other two smaller parties are against. (...) [A]nd then this will also happen on the other side if they win the elections, depending on what is the majority, if they are to bring in those two smaller parties (...) they will go for a ban (...) we don't know... but in the meantime we have this observatory and we are going to use it for testing both software and also hardware technologies*."

He then points out how the political issues at stake are smoothed because the project is strongly promoted by the IMR. The IMR plays a particularly significant role: on the one hand, it has a vast knowledge base of marine biology and oceanography. As a result, it is cardinal to NorthOil's agenda:

> *"[The Venus project] is an initiative that is promoted strongly by the [IMR] (...) And also because our ambition is that in order to be able to do a good job if it is opened, we need to know as much as possible about the natural conditions (...) It if is opened it will give us a much better basis to operate safely in the area."*(ibid)

On the other hand, the IMR, driven by a concern about the possible environmental consequences of an accident, is making use of the same project to demonstrate that the Venus region should *not* be opened to oil and gas activities. I did not have the chance to investigate the IMR's motivations in depth during my PhD project. I nonetheless note that this point is crucial. It makes it clear that the results of the same knowledge retrieval practices can be used in several ways, in this case, either to demonstrate that the environment in Venus should be preserved, or to demonstrate that it is possible to safely operate in it.

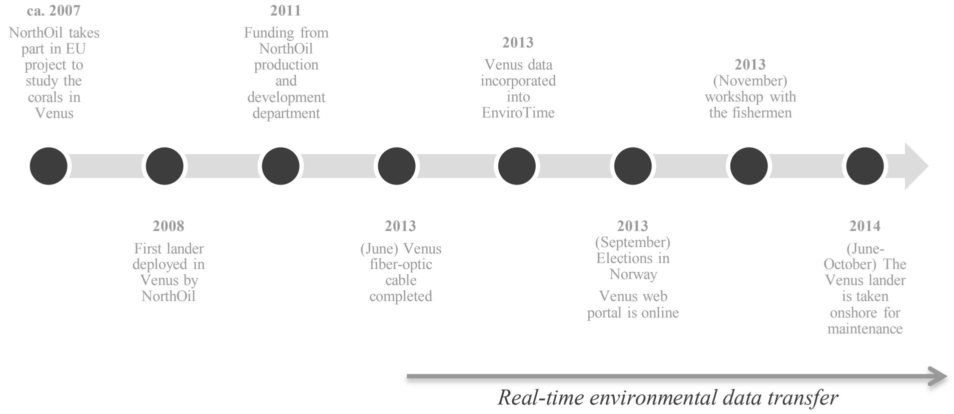

Figure 8. Timeline of the most significant events for the Venus project.

The Peter Ocean Observatory (Brazil)

When NorthOil acquired the Peter field in Brazil, the same group of environmental experts and the technology vendors (e.g., MAS) that took part in the Venus project worked on repurposing the Venus environmental monitoring solution for the Peter area. The first offline observatory was installed in 2009.

The key difference with Venus was that the observatory was set in an operational area, in the vicinity of a functioning oil platform. The seafloor in Peter is rich in calcareous algae. The goal was thus to detect any harm to the algae caused by the production activities. In this case, the monitoring station was not meant to send online data to shore, but the sensor measurements were stored on a hard disk located inside the observatory and retrieved for data analysis after a few months. The initial idea was to adopt a buoy for online satellite data transfer, however, the local fishermen would not respect the 500 meter safety distance from the oil platform and would use the buoy to anchor their boats while fishing. Ultimately, buoy-based online transfer did not prove a viable option.

In addition to these episodes, as we discuss in Papers 5 and 7, the 'Peter Ocean Observatory' experienced some technical failures which resulted into unusable results. The key reason for the technical failures was later discovered to be the natural characteristics of the Brazilian waters. Not only were they warmer than those in Norway, but the current was much stronger than environmental experts had expected. Upon analysis of one of the failures, the experts noticed that the metallic structure of the observatory and the sensors were being damaged. This meant one thing: the waters were very corrosive. If that was a problem for the small monitoring station, it was also for the whole oil platform. This finding therefore emphasized the importance of integrating environmental indicators in the daily oil and gas activities, because they may reveal dangers to the safety of the workers on the platform. Environmental risk thus proved a reliable indicator to assess technical and human risk.

3.3.3 Prelude to integration: GlobalMapping (2008-2012)

The path towards the integration of environmental monitoring practices in NorthOil does not begin with an environmentally related project.

In 2008 NorthOil began a large-scale data management integration endeavor (GlobalMapping) in collaboration with ITCorp to develop an integration layer for an enterprise-wide access to real-time plant- and equipment-related data. Originally a research and development project, it was early turned into a pilot implementation and shortly after into product deployment. The core to GlobalMapping was the realization of a top-down data model (or ontology) that would serve as a reference to map the data collected in all assets owned by NorthOil. The ontology was meant to serve the heterogeneous disciplines involved in oil and gas operations which could thus make used of a standard vocabulary to refer to or query information regarding operations and assets. This goal was not achieved. First of all, according to my informants, there was little preliminary experience in NorthOil with this type of project, so the requirement specification was not sufficient. Secondly, technical problems emerged early: it proved too complex and expensive to map the myriad heterogeneous local pieces of information to a top-down model. Thirdly, NorthOil and ITCorp disagreed on the maturity level of the GlobalMapping solution.

GlobalMapping was finally shut in mid-2012. I partly tackled this issue in Paper 1 (Parmiggiani and Hepsø 2013), but I have not been able to gather additional information. Even if it did not deliver the promised results, it represents an important step because it sensitized the company to the issue of an integrated approach to data management.

3.3.4 The corporate initiative: EnviroTime (2011-2014)

EnviroTime (November 2011-November 2014; see Figure 9 for a timeline) is a large-scale research and development project initiated in November 2011 by NorthOil, in collaboration with three industrial partners. EnviroTime was advertised in the newspapers and received much attention from media and external stakeholders. The goal was to develop what the internal documentation called a “flexible monitoring platform," a framework to meet a comprehensive set of field-specific challenges. It was presented as a decision-support solution "to monitor and analyze the environment in parallel with daily operations in order to protect sensitive areas and minimize the risk of potential negative impact on the environment." (Internal restricted documentation) It was the first corporate project in NorthOil with explicit focus on the management of environmental and technical data simultaneously, in real time when possible. This approach was mirrored by a conception of environmental monitoring that included not only ex-post assessment of the effects on environmental resources, but also the ex-ante control of discharges and the detection of leakages. Moreover, explicit attention was paid to the *continuous* nature of monitoring to address all phases of the lifecycle of a well: the early planning stages where no technical equipment is in place yet; the operational stages (drilling, production) where very old technologies and equipment might be available; and the decommissioning phase, where the well has run dry and the installation has to be removed completely.

NorthOil's industrial partners were organized into a consortium composed of:

- *O&GSolutions*, head of the consortium and in charge of providing:
    - information integration layer;
    - sensors and communication technologies;
- *QCB*, for:
    - maritime environmental analysis;
    - risk management practices;
    - setting standards in environmental monitoring;
- *ITCorp*, to provide business analytics technologies (e.g., hydrophone data analysis).

The consortium covered 50% of the expenses of the project. This significant joint financial effort demonstrated that integrated environmental monitoring is also a business case relevant to other big players in the Norwegian industrial sector.

The ambition of EnviroTime was to develop integrated environmental monitoring as a concept based on the data from a few test locations (e.g., Central Norway; later also Venus). Overall, the project treated environmental monitoring as an evolving and open-ended set of capacities to enable environmental coordinators – an emerging figure in the company – to halt operations instantaneously upon the identification of sensible resources. At the same time, other professionals also operating a well – such as the drilling engineers – must receive real-time updates on the environmental parameters in parallel with the well data streams that are part of their duty work. EnviroTime comprised the development or adaptation of subsea sensor systems comparable to the Venus observatory, integrated modeling software (e.g., based on the DREAM software), and organizational work processes.

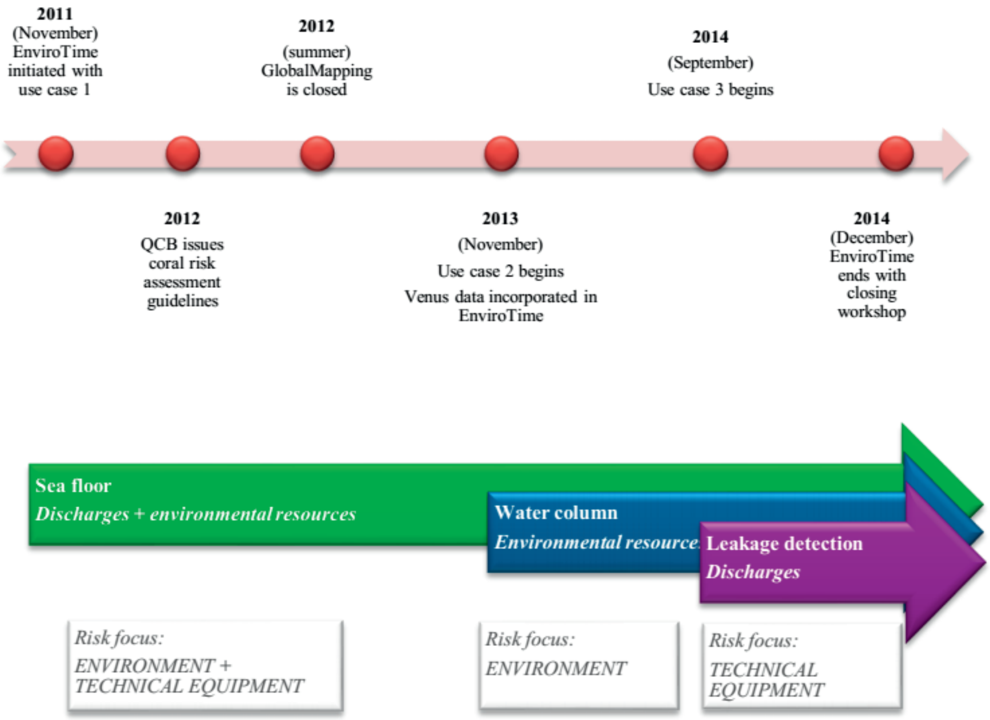

Figure 9. Above: timeline of the EnviroTime project. Below: context, object of monitoring, and, risk type for each use case. The arrows overlap to indicate that the discussions of a use case did not end with the initiation of the following use case.

The project had a hierarchical structure formalized into two main work packages. The first work package had to address the development or adaptation of a subsea sensor network into an ocean observatory similar to the Venus observatory. The second work package had a more sociotechnical focus. It was meant to develop or adapt software tools and integrate them into new work routines to fit daily operations. As discussed in the next subsections, the development of new work routines was later formalized as an additional independent work package.

The first work package had to deliver demonstrators of subsea ocean observatories. The second work package divided the internal focus into three use cases, identified previously as relevant to the company's business strategy:

1) Prevention of the dispersion of drill cuttings[15] into the cold-water coral reefs;

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[15] Materials of a heterogeneous nature removed from a borehole while drilling a well.

2) Long-term monitoring of the cod and herring and their spawning products in the Venus region;
3) The preventive detection of oil and gas leakages.

The two work packages proceeded in parallel, but my fieldwork focused primarily on the second work package (Use Cases 1 and 2).

As part of Use Case 1, a GIS-based web portal was developed to visualize real-time updates of the risk forecast for the coral reefs in the vicinity of an operational area, for example when drilling a well off Central Norway (see Figure 10 for an illustration). Online parameters sent from subsea sensors described the status of every reef, which was also colored in different ways (red, green, yellow) based on its health and contoured differently based on its predicted risk level. This web portal was dedicated primarily to the environmental coordinators in charge of the environmental monitoring campaigns and of assessing the level of environmental risk during the various operational phases (Figure 10, left).

Some of the real-time environmental data were also added to the web portal adopted by engineers in charge of a drilling operation along with the real-time trends describing, for example, the drilling speed (Figure 10, right). This use case was based on QCB's existing methodology for mapping the risk to cold-water corals based on the predicted amount and content of the discharge generated while drilling a well. The main method used to represent the risk to a reef was based on a risk matrix (see Figure 10, left). The coral risk matrix represented the probability of a coral structure being hit by drilling discharges against the predicted consequences on that specific structure (e.g., dead coral would suffer no consequence, so the risk would be zero). Such a methodology had, however, so far been based on offline sampling and primarily used to predict pollution prior to drilling. With EnviroTime, QCB's ambition was to turn it into a semi-automatic, real-time algorithm that could also run during the further phases of well development.

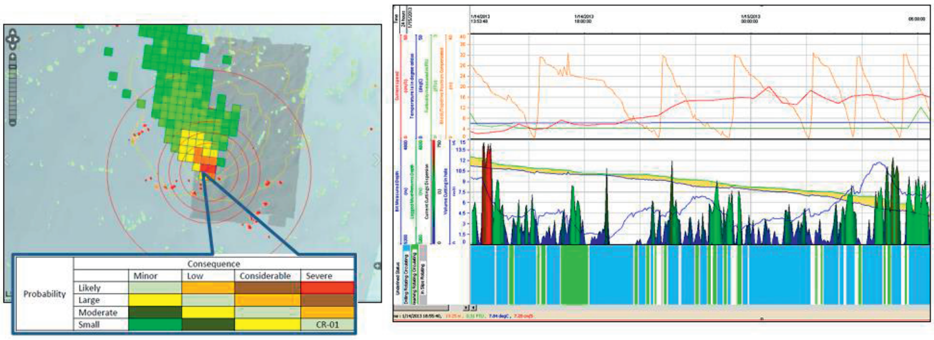


Figure 10. Illustrations of the functionalities of the EnviroTime portal for the environmental coordinators (left) and the drilling engineers (right) (source: own drawings).

Use Case 2 was focused on expanding the EnviroTime web portal to the long-term monitoring of biomass in the water. The problem changed from that of 2D mapping of the sea floor to a 3D description of the distribution and flux of biomass in the water column. In the same period, the first online data streams from the Venus Ocean Observatory became available. After a number of internal discussions and as a consequence of a delay in the EnviroTime schedule, it was decided to adopt Venus as the test location. It was at this stage (end of November) that EnviroTime and Venus became so entangled that the two projects began to inform each other and discussions often took place at the same time. As I will explain in the next section, the project manager of EnviroTime agreed to divert some project money for the development of a real-time web portal solution specific to the Venus observatory. In turn, the Venus data was adopted by EnviroTime and particularly used by QCB to develop the 'environmental value' (refer to Papers 5, 6, and 7). The environmental value represented the relative concentration of biomass at a point in the ocean, where 'relative' refers to the historical average concentration of fish in that point. Taking this as a point of departure, QCB began to develop a classification system of the status of the marine environment in a specific area. The system was inspired by the coral risk matrix (Paper 6 and 7).

The scope of the project saw several adjustments. For example, it suffered from external events. During the first semester of the project many human and financial resources were dedicated to the development of a shared semantic data model to represent all the possible environmental data to be handled during, for example, the drilling phase. As is clear from Table 2, this took place simultaneously with GlobalMapping. As the latter project was shut down, EnviroTime also went through an internal re-organization.

Although broadly concerned with turning the traditional risk assessment procedures into an integrated and real-time process, EnviroTime displayed different conceptions of ‘risk’ based on the use case. As shown in Figure 9, the first use case addressed risk as something related both to the environment (mostly the coral reefs) and to the technical equipment (the drilling rig). In Use Case 2, circumstances which led to setting the test location in Venus turned ‘risk’ into a fully environmental concern related to fish migration. Finally, although not directly addressed here, the third and last use case adopted a symmetrical approach to ‘risk’, this time only referring to failures of the technical equipment.

The data governance and stakeholder management work package

A strategy oriented to integrated environmental monitoring practices required institutionalizing a stricter collaboration between professionals with environmental and engineering expertise. The coupling of environmental and technical data in the EnviroTime web portal had to be mirrored by integrated work routines that encompassed both domains. Due to the strict requirements of reporting and accountability associated with oil and gas activities, this effort had to formalize the work processes at the corporate level. Consequently, NorthOil initiated a separate work package with the explicit target of adapting or implementing cross-disciplinary work processes for connecting environmental monitoring tasks to the existing workflows. Preliminary to this achievement was the formalization of detailed guidelines for governing environmental data; establishing decision rights, accountabilities, and methodologies for information management according to agreed-upon models. The work package continued in parallel with the main project for its duration and two of the EnviroTime participants from NorthOil were responsible for its completion (refer also to Paper 4).

These tasks consisted of much work to explore all the 30,000 official work processes adopted by NorthOil’s units and professional disciplines. It became necessary to establish a conversation with the representatives of the other sections (e.g., Drilling and Well department; environmental coordinators; GIS data managers; Arctic development program) with the joint goals of understanding their routines and thus enrolling them as stakeholders in the EnviroTime solution.

I was officially invited to the bi-weekly meetings arranged to discuss the evolution of this work package. I consequently had the chance to provide limited feedback on the documentation produced and to actively comment on the issues at stake. I was also invited to the face-to-face and teleconference meetings with the stakeholders from other NorthOil units. Two of the most significant meetings for this thesis took place with the Drilling and Well Department and with the Arctic Program, the latter in charge of facilitating solutions to improve NorthOil’s operations in the Arctic region.

The Drilling and Well Department was reluctant to endorse a change to their work processes, because they must comply with strict formal requirements governing the well construction process. During the conversation with the EnviroTime participants, the unit representatives stressed the importance of assessing the trustworthiness and reliability of environmental information as a prerequisite for them to become operational modifiers. Another interesting point relates to the focus of EnviroTime Use Case 1 on coral risk assessment. The Drilling and Well representatives pointed out that their formal work processes had to be applicable to each one of the well operations the company conducts around the world. On a global scale, only one fifteenth (sic) of the wells operated are close to coral reefs.

The Arctic Program had a different attitude due to the business relevance of environmental monitoring solutions for obtaining permissions to operate in the High North. The conversations particularly revolved around the need to define environmental data governance to obtain a better understanding of environmental conditions on the ice edge. In the words of the program responsible:

> "*The [Arctic] initiative wants to position [NorthOil] in the north and in particular the ice edge is a very good potato: they need food to position [NorthOil] in the North (...) [W]hat is interesting for the [Arctic] initiative is the issue of the ice edge, what resources are there, what can be visualized. There are many political aspects involved*."

This statement was made in February 2014. One year later, in January 2015, the Norwegian government redefined the edge of the permanent Arctic ice northwards prior to launching a new licensing round for oil and gas companies (Brønmo and Kagge 2015; see also Koranyi 2015). The key argument behind the decision was that ice has retreated considerably due to the effects of global warming.

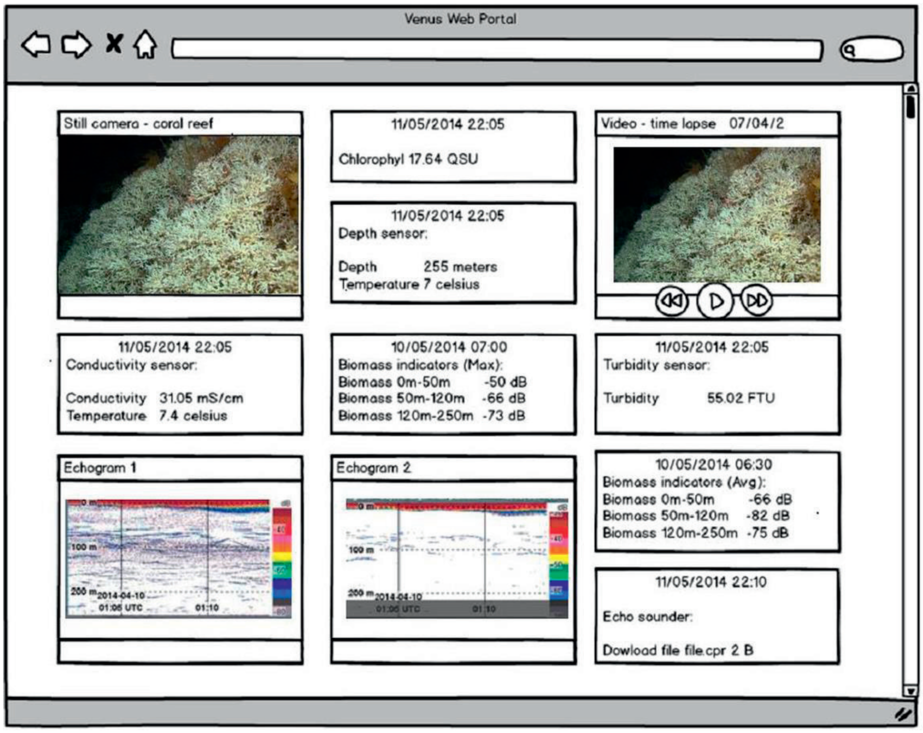
3.3.5 Venus reloaded: The Venus web portal

As suggested above, during the second half of 2013 the datasets from Venus were becoming available online, at the same time as EnviroTime was experiencing delays. The EnviroTime managers therefore used project funds to support the development of a web portal to display the Venus datasets. The development was conducted by a subgroup of environmental and IT experts in NorthOil in collaboration with marine acoustic experts from MAS and the IMR, and a consultancy company. The IT advisor who was primarily responsible defined it as a "*skunk works project,*" or an under-the-radar initiative that was not following the corporate decisional gates and procedures. Possibly also for this latter reason, in a few weeks the web portal was published online. The portal has a very simple layout (see also Figure 11 for an illustration). It is divided into three columns and displays pictures of the coral reef seen by the camera in Venus, a video of the latest pictures, two chromatograms plotting the concentration of biomass (fish, eggs, larvae, and zooplankton) in the water column above the Venus observatory, and the values of a few oceanographic parameters measured by the sensors. The online publishing of the real-time datasets is however never actually *real time*, but delayed by about four hours. The reason for this choice according to my informants is that the acoustic devices in Venus are also able to track the movements of ships and submarines of the Norwegian navy during military exercises. Since the datasets are also free to download and every ship or submarine has a unique acoustic signature, the online availability of the acoustic measurement would allow hackers to track the movements of the Norwegian navy in the area.

The Venus web portal is significant for two reasons.

Firstly, it represents the intersection of sharply contrasting interests. For NorthOil, the web portal is a good commercial tool for presenting the company's monitoring abilities to the authorities and the good will in preserving the environment to the general public. The IMR was very involved in the development of the portal, but with the opposite agenda of demonstrating that the area should not be open to oil and gas operations.

Secondly, it also proved a good political tool. As reviewed above, the Venus area is also of great interest to the Norwegian fishing industry. The members of the Venus project, especially from NorthOil's end, soon realized the importance of enrolling the fishermen as stakeholders in the initiative. It did not matter whether they agreed with an opening in Venus, but, as experience with, for example, the IMR showed, persistent disagreement was not an obstacle to successful collaboration (see also Paper 1 (Parmiggiani and Hepsø 2013) and Paper 6). A workshop was therefore organized in November 2013 to present the Venus portal to a community of fishermen in a small town near the location of the onshore data center where the Venus data were physically stored. The initiative was described by each of my informants as a success. A local newspaper also wrote an article about it, stating the web portal was becoming "more popular than the Disney Channel" and that "for the fishermen the observatory meant way more knowledge about the sea." (Erlandsen 2013) This event is specifically relevant because the feedback that the fishermen gave to the initiative was, maybe unexpectedly, very positive. A local representative of the fishermen indeed commented that he wished there were more such observatories in the area.


Venus Web Portal

Still camera - coral reef

11/05/2014 22:05
Chlorophyl 17.64 QSU

11/05/2014 22:05
Depth sensor:
Depth 255 meters
Temperature 7 celsius

Video - time lapse 07/04/2

11/05/2014 22:05
Conductivity sensor:
Conductivity 31.05 mS/cm
Temperature 7.4 celsius

10/05/2014 07:00
Biomass indicators (Max):
Biomass 0m-50m -50 dB
Biomass 50m-120m -66 dB
Biomass 120m-250m -73 dB

11/05/2014 22:05
Turbidity sensor:
Turbidity 55.02 FTU

Echogram 1

Echogram 2

10/05/2014 06:30
Biomass indicators (Avg):
Biomass 0m-50m -66 dB
Biomass 50m-120m -82 dB
Biomass 120m-250m -75 dB

11/05/2014 22:10
Echo sounder:
Dowload file file.cpr 2 B

Figure 11. A mockup of the Venus web portal for illustrative purposes (source: own creation, with www.balsamiq.com; pictures: MAREANO/Institute of Marine Research, Norway).

3.4 Research setting: NorthOil R&D department and the partner companies

Throughout this thesis I use the term ‘project participants’ to mean the employees from NorthOil and its partner companies who were directly involved in the design, implementation, maintenance, and administration in the projects listed above.

That said, the primary setting for my research was the NorthOil R&D department, in particular the newly established section for environmental modeling and monitoring which is part of the division for safe and optimized resource production.

The professionals I was most in contact with constituted a rather homogeneous group. Almost all had been involved in the environmental monitoring projects described above, but they had different backgrounds: in addition to environmental experts (educated in marine biology or environmental chemistry), I also had daily conversations with computer engineers (only some located in the IT department), data management experts, and anthropologists.

NorthOil R&D section was my primary research setting because it was where most of the discussion about EnviroTime took place. As a result, whereas I was primarily physically co-located with NorthOil employees, contacts with the employees of the other companies sometimes also took place via the videoconferencing system. A few weeks after I began my fieldwork I got in touch with the project participants from the partner companies. I was engaged in conversations during meetings or setting interviews with environmental advisors and data management experts from QCB. I travelled a few times to their headquarters, mostly to follow the EnviroTime general meetings and once to hold interviews in collaboration with my supervisor.

On two occasions (once with my supervisor) I visited NorthOil's Online Support Center (OSC) in person, not directly involved in EnviroTime but enrolled as a possible internal stakeholder. There I could interview and chat with data management experts and computer engineers.

Unfortunately my access to O&GSolutions and ITCorp was less successful. I was nevertheless able to chat with a variety of professionals from those companies during the EnviroTime meetings.

I was finally also interested in getting in touch with the environmental experts from MAS, the technology vendor involved in the Venus and Peter projects. I therefore contacted the head of the company headquartered in another Norwegian city. I spent one day there and was able to interview and chat with the marine acoustic experts. During the same trip, I also visited the IMR (also advising NorthOil in the same projects) and spoke with two experts in marine acoustics.

4 Research methods

NorthOil's current projects aim to establish a new capacity for real-time subsea environmental monitoring and integrate it with daily operations. As presented in the previous chapter, these endeavors serve multiple purposes and consist of adapting, developing, and integrating sensor networks, instruments, information systems, and organizational work processes. In other words, new infrastructural relations are being established and grown. An actor-network theory-informed lens recognizes that these efforts leave the boundaries of the new capacity only partly clear and under constant evolution. As a result, the main unit of analysis for this thesis is the *infrastructuring* mechanisms, i.e. the constant efforts to establish and maintain new infrastructural relations to upgrade NorthOil's infrastructure by integrating the new environmental monitoring capacities.

The research was conducted as a longitudinal interpretive case study. Case studies have been criticized for providing context-dependent and non-generalizable knowledge. As Flyvbjerg (2006) demonstrates, however, "[C]oncrete, context-dependent knowledge is (…) more valuable than the vain search for predictive theories and universals." (p. 224) Case studies are indeed useful in order to understand complex social phenomena and to investigate the holistic and meaningful characteristics of real-life events, such as organizational processes (Yin 2009). They can be seen as a form of problematization that associates the object of investigation, the motivations, and the research method (Beaulieu et al. 2007).

The purpose of this chapter is to reflect on the evolving relationship between these three dimensions. In the next section I describe the process of gaining access to the field site. I later present the research approach, the data collection, and the case study definition. I subsequently provide an account of the data analysis methodology. To conclude, I provide some reflections about conducting ethnographic fieldwork inside an oil and gas company.

4.1 Negotiating access

Access to case studies in the oil and gas business is not straightforward for external researchers. Despite the undoubtedly open attitude of Scandinavian organizations, the oil and gas business is a secretive setting, driven by the great political and economic sensitivity of energy strategies.

The negotiations to allow my access to the field site began prior to my enrollment on the PhD program and were facilitated by the Center for Integrated Operations in the

Petroleum Industry (IO Center[16]), a research-based innovation center supported by the Research Council of Norway and several international oil companies, NorthOil included. The IO Center also financed the PhD position. My case study is part of the Digital Oil project[17] headed by my supervisor and funded by the Verdikt program of the Research Council of Norway. Digital Oil studies the complex practices of operating subsea oil and gas wells over several decades in a safe and sufficient manner when activities are conducted through sensor-based information streams. Digital Oil involves a number of case studies corresponding to different phases in subsea operations, such as the exploration of new reservoirs, the exploitation of new data-transfer technologies while drilling, and the monitoring of the marine environment which surrounds a subsea operational area (this thesis).

Digital Oil obtained funds in late 2011. NorthOil also emerged as a relevant setting for the case study for pragmatic concerns, as my co-supervisor, who has an established connection with my main supervisor, works as a senior researcher in NorthOil. Through this collaboration, EnviroTime – which had just been initiated – was identified as a suitable case study for my research. Relying on the mediation of my supervisors I got in touch with the leader of the department in NorthOil R&D section where most EnviroTime participants were located. In April 2012 I was granted a badge and access to the department. I was initially allowed to use a shared desk in the hallway of the department, not far from the office where six participants in EnviroTime were sitting. To get acquainted with the people and the project, I initially followed them to the meetings they were attending. Throughout this chapter I will provide better insight into how my increasing familiarity with the research setting improved my data collection and the framing of my unit of analysis.

4.2 Research approach

This research adopts an interpretive stance derived from a hermeneutic tradition (Frodeman 1995; Klein and Myers 1999; Walsham 1995). Interpretivism in IS research assumes that our knowledge of reality is acquired through a process of social construction (e.g., shared meanings, tools, artifacts) and tries to understand empirical phenomena through the meaning that actors assign to them. In line with hermeneutics, interpretivism maintains that human perception of objects is always shaped by the set of tools, concepts, and expectations that we use in order to act on and conceive objects (Frodeman 1995).

The fundamental principle of the hermeneutic circle proposed by Klein and Myers (1999) is one of the compass points of this thesis. The principle states that "all human

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[16] http://www.iocenter.no

[17] http://www.doil.no

understanding is achieved by iterating between considering the interdependent meaning of parts and the whole that they form" (p. 72), where "the parts can be the interpretive researchers' and the participants' preliminary understandings (...) in the study. The whole consists of the shared meanings that emerge from the interactions between them." (p. 71)

Overall, these guidelines have two methodological consequences. First, they influenced my approach to the unit of analysis. I indeed understand NorthOil's environmental monitoring projects as more than an issue of developing new technologies (cf. Williams and Pollock 2012) but as the development of an infrastructure including new work practices and new knowledge. Secondly, I recognize that in my case study, both myself (the researcher) and the actors I observed are knowledge workers, tasked with producing knowledge objects by balancing subjectivity and objectivity (Schultze 2000). A direct result of this close relationship between the actors and the researcher is that they constantly appropriate each other's ideas in the field, as recognized by the principle of interaction between the researchers and the subjects (Klein and Myers 1999). This aspect, on the one hand, requires a critical reflection of the social construction of data (ibid). On the other hand, it blurs the boundaries between researchers and actors. I will elaborate more on these two points throughout this chapter.

4.3 Data collection

Various data collection methods can be used in interpretivist studies. My data collection was extensively inspired by ethnography with a fieldwork strategy (Forsythe 1999; Van Maanen 1988). Born and raised in anthropology to produce 'thick descriptions' of far cultures where the ethnographer would immerse herself for a long period, ethnography is today also accepted as a means to study modern organizations. Corporations hire ethnographers to gather qualitative evidence of the functioning of daily work (Hepsø 2013). Ethnography is today widely adopted in IS for the study of information systems in organizations (Myers 1999; see, e.g., Orlikowski 1991). It is also accepted within CSCW as important for highlighting the sociality and the materiality of work (Blomberg and Karasti 2013). Schmidt (2011) calls for more workplace-based ethnographic studies to gather a better understanding of the often sophisticated forms of ordering collaborative work.

Table 4. The sources of data collection (period: April 2012-December 2014). *Some NorthOil employees who took part in GlobalMapping were later involved in EnviroTime, too. If so, I counted them as EnviroTime participants in the table but the interviews covered both projects.

Source
Observations (3 years) • In-office co-location with 5 EnviroTime participants (ca. 3 days a week * 2 years; afterwards ca. 1 day a week * 9 months) • 49 meetings (teleconferences, workshops, seminars, briefing sessions) • 38 regular briefing sessions on data governance; EnviroTime status. • 14 events (conferences, seminars, workshops) related to the topics covered in EnviroTime but not strictly to NorthOil's projects. • Coffee and lunch breaks (every day spent at NorthOil)
Semi-structured interviews (38; average duration 1 hour) • 17 with NorthOil employees (engineers, environmental experts) participating in EnviroTime, Venus, and Peter • 4 with NorthOil employees participating in GlobalMapping • 9 with QCB environmental experts participating in EnviroTime • 1 with an O&GSolutions participant in EnviroTime • 2 with engineers at NorthOil OSC • 3 with marine acoustics experts at MAS • 2 with marine acoustics experts at the IMR
Documents • MS SharePoint team sites • Email exchanged in EnviroTime • Internet-based public information **Software** • EnviroTime web portal • Venus web portal • NorthOil Internal GIS system • Repository of internal work processes • Real-time data visualization portal for drilling engineers

Klein and Myers' (1999) principle of contextualization of interpretive research invites critical reflection on the context that gave birth to the situation under investigation. Accordingly, I strived to obtain diverse perspectives by triangulating three main types of data sources: participant observations; semi-structured interviews; and document analysis. Table 4 includes a summary of the data types and topics covered. This approach reflects Bowker and Star's point (1999; cf. Latour 1993) that it is important to look at both what actors say they are doing (e.g., through interviews, official documents) and what they are actually doing (e.g., through observations), also to be able to account for the way that scientific and political aspects mix in action.

Data collection activities began as soon as I was given a badge to the NorthOil R&D section in April 2012. Following an ethnographic approach (Myers 1999), the primary source of data generation were participant observations while sitting at my desk and during different types of meetings, workshops, seminars, in addition to lunch and coffee breaks. In the period April 2012-April 2014 I visited NorthOil on average three days a week during office hours, filling several pads with field notes. Through an extensive presence in the field, I was able to leverage one of the valuable aspects of ethnographic research, its potential for depth: “by going ‘where the action is’, the field researcher develops an intimate familiarity with the dilemmas, frustrations, routines, relationships, and risks that are part of everyday life.” (ibid, p. 5) From April 2014 to December 2014 I paid less frequent visits to NorthOil (once every one or two weeks) to keep the connection and ask follow-up questions to key informants. As I explain later in more detail, in November 2012 I began sitting next to some EnviroTime participants. In this way, I could follow discussions and conversations as they emerged over the day. I could also often join the EnviroTime participants when they travelled to the headquarters of the project partner companies in connection with meetings, seminars, project decision gates. All events were held in Norwegian. As a non-native speaker I learned the language during my first phases of fieldwork. In the first months I had to ask my co-supervisor (who also holds a position in NorthOil and was involved in the project) for clarification about anything I could not understand. Within a few months, I became an independent listener and could ask questions during the meetings in English. As my knowledge of Norwegian improved, I was later able to ask questions and give comments or limited feedback in Norwegian. In total I participated in 47 non-regular meetings, 36 regular meetings, and 14 events not directly related to my case study but still relevant to the topic of environmental monitoring in the oil and gas context.

Figure 12. My field notes (front) and the videoconferencing system used during a video meeting with another office of NorthOil.

The participant observations generated a snowballing effect that enabled me to identify key informants for semi-structured interviews (38 in total). To familiarize with the project, I initially held my interviews with NorthOil employees. In total I gathered 23 interviews with NorthOil employees, 2 of which were with the Online Support Center (OSC) in NorthOil's headquarters in another city. As soon as I became more acquainted with employees of the partner companies taking part in EnviroTime, I could schedule interviews with them, either via the MS-based videoconferencing system or by travelling in person to their offices elsewhere in Norway. Following a suggestion from a NorthOil employee I first interviewed the vice-president of O&GSolutions. I then contacted EnviroTime participants from QCB and held 9 interviews with them, 7 of which were also with my supervisor. In the last period of my PhD I tried to contact other EnviroTime members from O&GSolutions, but due to delays in the EnviroTime project this did not prove feasible. I then turned my attention to the sensor technology vendor (MAS) involved in the Venus project and other environmental monitoring programs run by NorthOil. That path proved easier and I managed to hold three interviews in MAS and two additional interviews at the IMR, with which MAS and NorthOil have ongoing collaborations. I often left the interview guide flexible to adapt to the conversation. To gain a better understanding of events prior to my entrance to the field site, I often asked my informants to provide a narrative overview of their involvement in the environmental monitoring projects, the events they could recall, and their perspective on how the various players related to each other.

Collection of internal (often restricted) documentation was a supporting empirical source throughout the whole fieldwork activity. I had access to the internal MS SharePoint team sites where all the documentation related to EnviroTime and other environmental monitoring programs was uploaded: in particular project deliverables, reports, and PowerPoint presentations. Documents were generated by NorthOil and by the partnering companies (QCB, O&GSolutions, ITCorp), in addition to technology vendors and consultants (e.g., MAS, the IMR). These documents were fundamental to understanding the technical details and the reasons for the choices made in every project. Documents (e.g., regulations, guidelines, reports) issued by national or international authorities were also a resource by which to contextualize NorthOil's strategies. Finally, internal or public documentation available via the NorthOil intranet portal was an additional source used to position the company's activities and business strategies. It proved, for example, a valuable tool to keep track of the new reservoir discoveries and drilling activities carried out by NorthOil in the High North. All documentation was organized in chronological order and classified based on source in order to better characterize the temporal unfolding of my case study. Together with the interviews it was the source for the generation of the timeline presented in Chapter 3.

A secondary but important data source was the ethnography of the software that was being developed in EnviroTime and Venus. I could, for instance, access and use the test versions of the EnviroTime web portal to visualize the real-time risk to cold-water corals and, in the same time, follow online updates from all subsea environmental sensors integrated into the portal used by the drilling engineers. By focusing on the EnviroTime portal, for example, I became aware of the emergence of the environmental coordinator as a powerful figure in oil and gas activities, now sharing the spotlight with the drilling engineers. I also made extensive use of the information available on the Venus web portal. Its development proved a useful starting point for scheduling interviews with the Venus project participants.

> ***A snapshot from the fieldwork: An example of data triangulation****. In November 2013 my supervisor and I interviewed two environmental experts at QCB headquarters. Towards the end of the interview we came to discuss the Venus project. One of the two interviewees remarked that the Venus acoustic devices are placed on the sea floor and this makes it difficult to spot eggs or larvae which are rather small and float close to the sea surface. The expert also pointed out "the fish experts… they do not have any experience about having the sensors [placed on the seafloor]." To make sure I understood correctly, I asked again: "So there is no experience whatsoever of using echo sounders from bottom to top?" And he firmly replied: "No."*
>
> *A couple of months later, I was attending a joint seminar in another Norwegian city with all EnviroTime participants. One expert in marine acoustics from O&GSolutions gave a speech to explain to the others – all with different background expertise – the difficulties of spotting small resources such as eggs or larvae from a long distance with the devices available in Venus. He confirmed the statement of the QCB expert.*
>
> *Almost one year later I visited the headquarters of MAS, the company that produces the subsea sensors used in Venus. The original plan was to obtain a better insight into the function of subsea sensors based on their experience. When I introduced my research and some of my findings to them, I also showed a PowerPoint slide a summary of the information I had received earlier about eggs and larvae detection. When the head the company saw it, he stopped me and commented that it was not true. Their company is capable of doing that and also has experience in environmental monitoring with subsea acoustic devices. I am puzzled; I was sure I had heard the opposite on other occasions.*
>
> *Back in the office, I went through the official documentation delivered by QCB in EnviroTime, where a pool of environmental experts explained mathematically why the detection of eggs and larvae is complicated in Venus with the devices available to them. I therefore concluded that the reality might lie in the middle. Given the long-term business relevance of the EnviroTime solution, the environmental experts involved are very cautious about letting me know very much about what they are able to do. Alternatively, more simply, this type of expertise is quite new for those in EnviroTime, so they still lack data and experience.*

4.4 Between data collection and data analysis: An application of infrastructural inversion

4.4.1 Case framing

The definition of the unit of analysis evolved during my project and adapted to the changes that I encountered during the fieldwork. As presented above, the initial driver of my case study was the EnviroTime project. When I began my fieldwork it was difficult for me to familiarize myself with the scope of project, however, I soon realized that it was unclear to the project participants as well. Initially many resources were in fact devolved by NorthOil and its partners to the development of a common ontology, or data model based on semantic technologies and aimed at describing the different data types to be handled by the new infrastructure. Accordingly, I focused my case study on the process of ontology development. The assumption that this was the right path for EnviroTime began to be questioned after the failure in late 2012 of a parallel project (GlobalMapping) to develop a global model of production and asset data run with some of the same project partners (see Section 3.3.3). This event triggered a change of trajectory in EnviroTime. A greater focus was now placed on developing integrated environmental monitoring as a concept supported by a few test solutions in, for example, North and Central Norway. I therefore began to adapt my case towards that which I am presenting in this thesis.

At almost the same time, another episode enabled me to gain closer insight into the activities of EnviroTime. As a consequence of the reduced lack of focus on ontology development, one project participant left, and from November 2012 I was able to use his desk in the office where my reference persons were located. As my familiarity with them improved, I gained access to further information and in mid-2013 I began to investigate other environmental monitoring programs run by NorthOil, such as Venus. EnviroTime was still an important case, but it was now embedded in a broader picture.

As a consequence I re-framed my case study as the ongoing evolution of an infrastructure for subsea real-time environmental monitoring in NorthOil. This includes the development or adaptation of technologies and methods used to collect and visualize environmental data. Embedded units of analysis are EnviroTime, Venus, and, to a limited extent, Peter and GlobalMapping.

At this point I was, however, left with two problems. Focusing an infrastructure implies that the boundaries of the inquiry (namely what is included and what is left out) remain, at best, blurred. Secondly, as noted by Williams and Pollock (2012), empirical studies of design and implementation in the IS literature tend to suffer from a number of limitations at the level of temporal and spatial framing, identification of key intermediary actors, and analysis of actors' strategies in a technological domain. This triggered a methodological issue, because the physical location of the data collection did not equal the field site: by sitting mostly in one place for three years, how would it be possible to tell a large-scale story spanning a broad temporal scale? I overcame this problem by adopting the concept of infrastructural inversion (Bowker 1994; see Chapter 2), which implies a 'gestalt switch' (Bowker and Star 1999) to shift the attention from the artifacts and tools with which users interact, to the overall infrastructural work that builds and sustains them (Graham and Thrift 2007; Monteiro et al. 2013; cf. Appel 2012).

Acknowledging that the researcher ultimately plays an active role in constructing the site of inquiry (Blomberg and Karasti 2013), I will now reflect on how I operationalized an infrastructural inversion in the temporal and spatial bounding of my case.

The temporal understanding of case studies is not a trivial issue. Within IS for example implementation studies tend to be too short to account for the extended time frames of technology innovation (Williams and Pollock 2012). As also pointed out within anthropology, the field site is better understood as a process of configuration of space *and* time in order to generate new analytical terrain (Dalsgaard and Nielsen 2013). When the focus is on networked systems such as infrastructures, the temporal flow is an important organizing principle (Beaulieu et al. 2007). Ribes and Finholt (2009) explore how infrastructural work unfolds as a set of tensions between the non-overlapping temporal scales of infrastructure (institutions; technology enactment; and organizing work). The '*when'* – rather than the 'what' – of infrastructure is the question we should answer (Star and Ruhleder 1996). As we discuss in Paper 6, to be successful the infrastructuring process must also balance the different temporalities of the heterogeneous human actors (e.g., the drilling engineers work unfolds in terms of seconds) and non-human elements (e.g., environmental cycles span decades). The timeline presented in Chapter 3 is an attempt to account for the way that mismatching temporal framings are inscribed in the infrastructuring process.

As far as the spatial framing is concerned, Williams and Pollock (2012) noted that implementation studies are often constrained to one or a few specific physical sites and therefore tend to black box related settings. The story of real-time environmental monitoring infrastructure in NorthOil is not only a long-term one, it is also distributed across different sites. The monitoring programs took place in different locations and the participants I interviewed were distributed across Norway. A project such as EnviroTime was purposefully meant to handle different operational phases in different geographical context. I asked myself: *Where* is the case happening? Studies of infrastructure problematize the reliance on physical space to constitute a case study (Beaulieu 2010). I realized that the case site equals the infrastructure under development. It encompasses the offices where decisions are taken, the offshore sites (fish and coral included), and the sensors and data models used to collect and represent data from the sea floor. The practical consequence of this, however, is that the *place* of knowledge production and its penetration by the ethnographer are no longer aligned (Beaulieu et al. 2007). I add that the same applies to the *time* of knowledge production.

I will discuss how I overcame this misalignment in the next paragraph.

4.4.2 Follow the actor, revisited

I have admittedly benefited from a good relationship with a small group of actors, primarily from NorthOil. Williams and Pollock (2012) however warn researchers from foregrounding only certain kinds of players and background others – a possible consequence of the Latourian "follow the actor" strategy (Latour 1987). In a nutshell, "following the actor" is a methodology proposed in actor-network theory (Callon and

Latour 1981; Latour 1987, 2005) to trace the movements and activities of the single actors in the field and to explore how actor networks are created. One example of the usefulness of this approach, according to Latour (1987), is the observation of how science is actually done. When observed in their daily practice, scientists are not hidden in bunkers ready to defend their claims. They must build and maintain a vast web of connections, for instance to obtain funding to conduct their studies. Latour traces the itinerary of a laboratory director travelling to the fund providers, convincing them of the alignment of their mutual interests, and making his claims public through the media. According to Williams and Pollock (2012), however, "this approach has been less successful in developing the more complex mappings and understandings that meet the above call that these solutions need to be studied over time and across space." (p. 2) Throughout my research, I indeed had to constantly address the scale of infrastructure while being, most of the time, a single researcher. Williams and Pollock propose a shift of perspective, and instead following the artifacts through space and time. I however decided to preserve the inspiration from actor-network theory to operationalize the infrastructural inversion. My point of departure is therefore that the "follow the actor" approach is still functional – it just needs adaptation. I did so for two reasons. First, empirically, given the initially blurred boundaries of NorthOil's EnviroTime project, it proved cumbersome to identify which artifacts to follow. Objects often changed shape. One example is the EnviroTime common ontology that would ensure semantic interoperability between various datasets. Whereas in the early phases it seemed as though the ontology would be one of the key deliverables of EnviroTime, after a few months it was no longer under focus in favor of other forms of interoperability, such as the guidelines for environmental data governance (see Chapter 3 and Section 4.4.1). The "follow the actor" approach also seemed more appropriate in the light of the theoretical framework I introduced in Chapter 2, in particular the definition of environmental risk (see Section 2.1). If we stick to a conception of risk as the consequence of human knowledge, then it might be useful to investigate how humans develop knowledge to "recognize and present problems as problems at all, or just not do so." (Beck 1992, p. 163)

According to Kaltenbrunner (2014, p. 4) "infrastructure, we could say, is the crystallized accumulation of [the actors'] historical articulation work." If we take the hermeneutic tradition in interpretivism seriously (Frodeman 1995), infrastructure becomes both the researcher's space of inquiry and the space of activities for the actors. Consequently, the distinction between the researcher and the actors is also less sharp and infrastructural inversion can be seen as a generalization of the concept of articulation work (Paper 4; cf. Schmidt and Bannon 1992). In other words, I was in the same boat as my informants. I therefore took inspiration from their strategies to tackle the infrastructure as a whole. If the case site equals the infrastructure as argued above, those characteristics of an infrastructure that make it difficult to frame (distribution;

digitalization; long term) are not only the object of investigation but become a resource for the fieldworker (Beaulieu 2010; Bowker and Star 1999). Ethnographers can align with specific actors – or “infrastructural allies” – to solve problems of scaling and “to get access to the backstage of infrastructures.” (Beaulieu 2010, p. 461) With this perspective, researchers should ask themselves how the actors in the field address the scale of infrastructure:

> “The key insight in this method is the recognition that anytime there is a ‘large’ endeavor you will find actors tasked with managing the problems associated with its scale.” (Ribes 2014a, p. 158)

Through extensive observations, I identified a cardinal subset of actors who, as part of their daily work, were in charge of answering the same questions I had to answer as part of my research.

One example was the data governance and stakeholder management task conducted in EnviroTime (see Section 3.3.4). It would have not been feasible for me, alone, to mine all the historically accumulated work processes used in NorthOil, exceeding 30,000, and to identify the spokespersons of every department in the company to discuss the possible integration of the new routines. Due to the good relationship established with several NorthOil employees during the participant observations, I was able to ‘piggyback’ two of the participants as they mined the work process and identified, contacted, and interviewed the representatives of other departments at NorthOil.

In parallel I also relied on more time consuming and expensive ways of scaling the data collection method by travelling by plane to other Norwegian cities to interview employees of other offices of NorthOil or other companies (e.g., QCB). The establishment of an initial face-to-face contact was subsequently useful in creating a ‘snowball effect’ and to gain access to information and important meetings and workshops. The face-to-face strategy was also important to tackle the last risk identified by Williams and Pollock (2012), namely a tendency to black box the sites of technology production. Following the suggestion of one important infrastructural ally at NorthOil, I obtained the contact information of a reference person inside MAS – the company supplying subsea sensors to NorthOil in Venus and in Brazil. I contacted him directly, and a week later I spent a day in his company in another city. There I could speak to other sensor and software experts, see and touch the sensors used in the Venus Ocean Observatory, and obtain an insight into that company’s perspective on NorthOil’s projects.

Before moving on, I would like to reflect on a corollary of infrastructural inversion that became clear as I was striving to find methods to scale my research activity. When attending events with more than one actor involved I realized that much of the work was scientific work, but it was done in a corporate setting. My informants have different backgrounds mostly belonging to the realm of science (e.g., marine biology, environmental chemistry, computer science). Their roles have emerged, however, with very different nuances, based on where they are employed. They are employed not only by research institutions (the IMR), but also by an oil and gas operator and by sensor vendors and technology providers (e.g., O&GSolutions and MAS) with defined commercial interests. It would be naïve to classify them in separate compartments based on their company membership, however, as it would be naïve to discard the science done within companies as second-order science. The joint arenas afforded by projects such as EnviroTime or Venus make clear that science and commercial enterprise can no longer be considered distinct worlds. Rather, scientists meet within corporate arenas and bring their educational training with them. It is through this amalgam that infrastructure evolution takes place and knowledge is constantly questioned, rethought, and generated. Phrased in the words of Bowker (1994), it is the connection between the organizational work *and* the scientific work that allows for infrastructure to emerge and grow.

Another corollary of my adaptation of the “follow the actor” approach is that I was able to address an additional problem identified in the recent literature, for instance within sociomateriality: How to account for the performative stance of materiality? Should material elements be, for instance, allowed to speak for themselves? (Cecez-Kecmanovic et al. 2014) NorthOil’s projects emphasized the primary role of, for example, cold-water corals, fish, and other non-human elements which were at the center of almost all conversations, interviews, and documentation. It makes heuristic sense to look at humans and materials as having the same type of agency, but as clarified by Callon and Latour (1992) we do not assume that material actors have agency. In practice, it is humans who decide what ‘voice’ will be granted to material elements (e.g., the corals, the cod) by enrolling a number of spokespersons to generate certain claims for consideration inside a collective (e.g., the oil and gas business). Importantly however, this point does not imply that materials are puppets for skillful puppeteers. As Latour clarifies,

> “When a force manipulates another, it does not mean that it is a cause generating effects; it can also be an occasion for other things to start acting. (…) So who is pulling the strings? Well, the puppets do in addition to their puppeteers. (…) The interesting question at this point is not to decide who is acting and how but to shift from a certainty about action to an *uncertainty* about action – to decide what is acting and how.” (Latour 2005, p. 60 emphasis in original)

By going through what Latour calls a ‘due process’ (Latour 2004), the claims generated by spokespersons might be considered useful and accepted as part of a new configuration of the collective. Latour’s conception of due process can therefore be applied to understanding how stakeholders are excluded or included in securing the rights of *some* subsea creatures. Methodologically, I therefore looked at my infrastructural allies also as spokespersons for the material elements of the infrastructure. They are, for example, the engineers and scientists whose daily work is to construct and distribute the properties of material elements (Callon and Latour 1992). I was thus able to follow the due process granted to Lophelia corals, cods, and calcareous algae which went from undifferentiated nature to the object of constant scrutiny and part of a sociomaterial entanglement of local political agendas, business needs, scientific interests, and technological innovation.

Figure 13. A dead portion of calcareous algae (material) on the desk of one of my informants (its spokesperson?).

4.5 Reflections on the role of the researcher in the field

In the three years of my PhD project I spent a considerable amount of time in the field. The purpose of this section is therefore to provide a few reflections based on my experience inspired by a confessional approach to revealing my role and acknowledging my personal experience and subjective engagement (Van Maanen 1988; Schultze 2000).

Dealing with an unknown world

As I began my field work, I encountered two main challenges: a unknown domain of study and a new language.

The oil and gas domain was in fact completely new to me. This meant that as I was encountering technical terms related to petroleum science and engineering (the first one being, as I recall, “Christmas tree,” i.e. an assemblage of devices used in wells and that look like a tree), I had to ask someone for clarification or look up the terms online and search the NorthOil intranet for documentation on the matter. The other domain with which I had to get acquainted was marine biology, however, since most discussions revolved around acoustic measurements, I could make use of my background at high school and university levels to understand the basic issues.

The second and possibly more demanding challenge I encountered was the language. I started my fieldwork two months after moving to Norway and after only a few classes of Norwegian. I initially had to take interviews in English, but I could not ask to hold the meetings I attended to be held in English: that would hamper daily work and would not allow professionals to express their ideas as they could do in their mother tongue. As a consequence, when strictly necessary I would ask people to repeat a concept, otherwise I would ask someone after the meeting to double check that I understood enough. As my knowledge of Norwegian improved, my data collection process accelerated accordingly. It was also easier to gather important pieces of information during coffee breaks or at lunch time. I held the last interviews only in Norwegian.

Improving access

> ***A snapshot from the fieldwork: Looking like a NorthOil employee.*** *In April 2013 a workshop was organized in the headquarters of NorthOil (in another Norwegian city) to discuss the possibilities of setting up a collaboration with a number of research institutions on the topic of semantic technologies. A few NorthOil employees from the IT department would provide their insights and the company's experience with semantic data modelling. When I was informed about the event, I was eager to participate, given both my past experience with semantic technologies and as a valuable data collection source for my PhD. I was soon informed, however, that I could not participate because my university was not directly involved in the project proposals. I did not give up, and asked one of my infrastructural allies in the IT section – whom I knew would take part in the workshop via the videoconference system – if there was any chance I would be allowed to participate. He looked at me with a surprised expression, and said: "Of course you can, you count as a NorthOil employee!" I did not expect this reply, but thanked him and joined the workshop. During the first round of presentations of the participants, he introduced me as one his collaborators.*

A second interesting aspect dealt with the increasing ease I had in doing my fieldwork. Due to my frequent presence at NorthOil, people became increasingly friendlier. After a short while I had gone from being 'the external researcher' to a 'piece of furniture' in the background. I did not sound threatening to the subjects in the field. Within less than a year and a half, and as my knowledge of Norwegian became good enough, I was actively enrolled in a number of sub-tasks in EnviroTime, such as setting up new work processes for environmental data governance. I could comment on documentation and support the person responsible for the specific sub-task.

As a consequence, I went from being a piece of furniture to something more. I was often mistaken for a full-time NorthOil employee by the real employees on the field site. I would then have to explain my actual position, but I did not experience a change of attitude towards me. My growing resemblance to a normal NorthOil employee and the fact that I always joined the general meetings along with NorthOil employees could have had an unwelcome side effect: the employees of the partner companies could have felt uncomfortable when sharing their thoughts with me, because I had the possibility to reveal everything to NorthOil afterwards. I admit that on a few occasions interviewees were uncertain of my role. Once I was directly asked if I would go back and report everything to NorthOil. After clarifying my position of researcher from an independent institution, however, the interviewees generally felt more comfortable in speaking to me (and to my supervisor when he joined me in the interview process).

4.6 Data analysis

During my research activity I collected a large amount of empirical data in different forms. Observations generated handwritten field notes, interviews mostly resulted in computer transcriptions, and documents were printed and organized chronologically in folders. As my familiarity with NorthOil employees increased, they would provide me with documentation and links to websites that were also bookmarked and organized chronologically.

My data analysis process was inspired by Klein and Myers' (1999; cf. Walsham 1995) guidelines to interpretive research. The aforementioned principle of the hermeneutic circle allowed me to maintain a degree of openness towards my data. The evolving relation between the 'part' and the 'whole' allowed me to change the unit of analysis for given purposes. The 'part' could be the engagement with a specific architectural element (semantic data model) and the 'whole' the information infrastructure the element was meant to represent (Paper 1 (Parmiggiani and Hepsø 2013)).

Also triggered by the process of paper writing and publishing, I constantly alternated data collection with data analysis. Data analysis was mostly conducted in three ways: at the personal level (in most cases); during conversations with my supervisors, especially when they were partly involved in the collection of the data; and during discussions with other members of my research group (sporadic), also engaged in case studies in the oil and gas domain (even if with different scopes).

In all cases the data analysis was conducted by interleaving inductive coding moments with theoretically driven deductive elements. I will now elaborate first on the inductive process and then on the theoretical influence.

The inductive part of my analysis followed the guidelines by Emerson et al. (2011) for coding and writing up ethnographic data.

The overarching approach to making sense of data – in line with interpretivism – is to always try to pursue the actors' meanings. Accordingly, even if it happens that ethnographic writing is filtered by the researcher's previous experiences and commitments, the analysis should be sensitive to local meanings and avoid imposing exogenous categories (e.g., following official rules or norms). This point is crucial and easy to forget. For example, during one of my first interviewees with a marine biologist at NorthOil, I collected the following statement where she described the current approach to handling environmental data during underwater environmental monitoring:

> *"Yeah and we have... depending on who did the surveys it is stored in different systems and to some extent the videos, they are not stored in any system at all because there is just a link to them... you find them on disks... So the more I have worked with the [XYQ] case the more I see we definitely do not have the system to get access to all the existing data either... of course those who use these data on a daily basis and those who collect this type of data, they know where to find it. But for environmental related issues it's already a lot of information that is collected in [NorthOil] but since they are collected for different purposes than environmental purposes, then environmental people do not have access to it or it is very hard to get access to it because it's hard to get hold of the data because either you need to know people to get access to disks, you need to know the system well to access these data. From my point of view as long as data is not easily available to different databases that can take all information from other databases then in practice these data is not available for the people in the company. I think it's even worse to have data that are not accessible than to not have data at all. In that perspective what you are doing is essential, because if we do not have a good system to take... to combine information from different databases, then we do not have anything to work with." (Marine biologist, interview, November 2012)*

I initially coded this except as *Immature environmental monitoring approach*, however, while discussing this point with another researcher, I realized that defining the approach as "immature" was my own categorization, not the interviewee's. She was indeed not comparing the current state of things with something which would instead be the "mature" approach, but rather providing the characterization of a work practice. The interview was taped, so I was misled by the frustrated tone of her voice when I made this interpretation. As a consequence I changed the open code into "*Current environmental monitoring work practice.*" When I was able to collect data on the new approaches to environmental data management I could say that the approach described by the biologist was immature. Nonetheless, I had to recognize that this was my own construct, not hers.

Emerson and colleagues (2011) also warn researchers against formulating the actors' meanings as facts, rather than what they are: formulations of (situated) social constructions. I came across this issue as I began to follow the work package on data governance in the EnviroTime project:

> *Interested in seeing who else in NorthOil took similar initiatives, I began to query additional documentation on "data governance" in the company intranet, perhaps to see if other departments had similar tasks, but I was not able to find much. Later, during one of the biweekly meetings on the topic, the person responsible for the task began to type the same query into the intranet. He also could not find anything. An IT advisor who took part in the meeting noted that what is called "data governance" in the context of EnviroTime normally goes under the name of "information management" in the rest of the company and so it was categorized thus on the intranet.*

While acknowledging that the actors' meanings must be pursued but never considered as uncontested facts, it is fundamental to maintain sensitivity to the possible differences in interpretations expressed by different actors (the principle of multiple interpretations

(Klein and Myers 1999)). During three years of fieldwork, I dealt with various cases where different actors – often from different companies – expressed incompatible narratives or accounts of particular events or motivations.

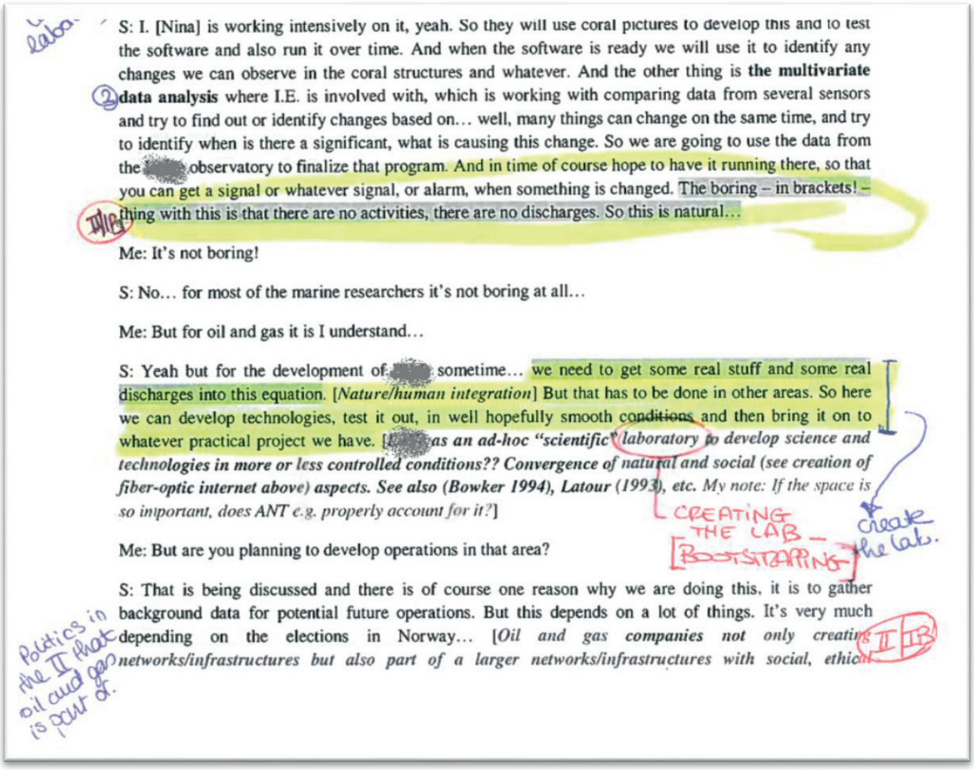
> ***One event, multiple interpretations**. Towards the end of 2013 an environmental expert and one IT advisor from NorthOil took part in a workshop to present the Venus web portal to a community of fishermen from a small town of north Norway close to where the Venus onshore data center was located. Two marine acoustics experts from MAS took part in the event. Since I could not join them in person for the workshop, I had to rely on their narratives of the event and on an article published in a local newspaper. The newspaper article provided an enthusiastic account of the event, presenting the Venus web portal as something that was "useful for the local fishermen" to get a better overview of the amount of fish in the water column.*
>
> *Back in NorthOil, one of those who took part in the workshop reported during a weekly debriefing session with his colleagues that the fishermen had commented that the chromatogram displayed on the Venus website was difficult to understand (a chromatogram is a graph based on echo sounder reading where fish concentration is plotted with reference to time and depth and colored in different ways based on density). I duly noted this remark, until during a meeting in MAS one marine acoustics expert who had taken part in the Venus web portal workshop told me the opposite: the fishermen quite liked the chromatogram, because they usually adopt commercial echo sounders to track fish. At this point I was a little puzzled, as the two accounts did not match.*
>
> *I therefore asked a NorthOil IT advisor who went to the workshop to give me his personal opinion of what happened. He told me that the fishermen did like the chromatogram, however, they found it a little difficult to read because they use portable devices to display the echo sounder readings, so the chromatograms they generally have to interpret are smaller and visualize narrower areas of the water column which gives a more pointed indication of what is fish and what is not fish. Nevertheless, they understand the Venus chromatogram as well.*

My conclusion from this example was not to take one of the accounts as the right one. I limit myself to recording that 'truth' has multiple versions which are reported by actors who come from a different organizational (a newspaper, NorthOil, MAS) and disciplinary (popular, marine acoustics, IT) backgrounds.

Inductive analysis was also informed by theoretically driven deductive elements. As noted by Klein and Myers (1999, pp. 198–99): "it is misleading to dichotomize data and theory as two separate and distinctive entities, as data are never pure but, rather, are imbed with, and structured by, concepts in the first place." The ethnographer has indeed prior analytic commitments: "[T]he ethnographer creates, rather than discovers, theory." (Emerson et al. 2011, p. 199) The theoretical interest underpinning my doctoral work was made primarily of research on information infrastructures and environmental risk at the crossroads between IS, CSCW, and STS (see also Chapter 1). As indicated by Eisenhardt (1989; Walsham 1995), theory can serve different purposes in research. In some cases, the analysis was iterative, driven by manual coding but with visible deductive influence (see Paper 5 for an example). In other cases, the inductive element was stronger and theory would be a more visible final product (see Paper 4 for an example). Finally, in some cases a theoretical framework drove the initial part of the analysis (see Paper 1 (Parmiggiani and Hepsø 2013) for an example).

Here follows a detailed summary of the inductive-deductive steps I usually took to analyze field notes, interviews, and documents (see Figure 14 for a snapshot from the field notes):

- I embed comments in the text (in the case of interviews, often already while transcribing or right after reading the transcription) with the ideas that come into my mind. If an excerpt reminds me of something I have read in a book or paper I refer to it in the comment – this phase is dependent on inspiration;
- I underline with different colors key sections that relate to different macro topics (e.g. the Venus project rather than the Brazilian project), so that I am visually able to find one part of the text quickly afterwards (my transcripts are mostly more than 10 pages each);
- At this point I generally print out the file and begin to go through the text. I annotate a summary of the topics covered in the left or right margin. This is a habit I have from middle school and I always do it when I read something for study or work. I might occasionally code both in English and in my mother tongue (Italian);
- In the same phase I also draw a circle around the keywords, for instance to identify periods or dates to build the timeline of my case study (as in Section 3);
- I then go through the text again to do the open coding. Codes might be acronyms (e.g. “II” stands for “Information Infrastructure” and “IB” for “Installed Base”). In this case what happens varies greatly. Initially I usually proceed inductively and add the codes to the text margin. They are generally in capitals, or in red, or anyway easy to distinguish from the other comments;
- In later moments (e.g., during an additional round of analysis when writing a paper) I also proceed more deductively by looking for theoretical constructs (e.g., “Bootstrapping”);
- When I am finished with these steps, I generally compare the results with previously coded data to compare and contrast the codes. This process is generally supported by discussions with other members of my research group.



labo

S: I. [Nina] is working intensively on it, yeah. So they will use coral pictures to develop this and to test the software and also run it over time. And when the software is ready we will use it to identify any changes we can observe in the coral structures and whatever. And the other thing is **the multivariate** ② **data analysis** where I.E. is involved with, which is working with comparing data from several sensors and try to find out or identify changes based on… well, many things can change on the same time, and try to identify when is there a significant, what is causing this change. So we are going to use the data from the [redacted] observatory to finalize that program. And in time of course hope to have it running there, so that you can get a signal or whatever signal, or alarm, when something is changed. The boring – in brackets! – thing with this is that there are no activities, there are no discharges. So this is natural…

II|B

Me: It's not boring!

S: No… for most of the marine researchers it's not boring at all…

Me: But for oil and gas it is I understand…

S: Yeah but for the development of [redacted] sometime… we need to get some real stuff and some real discharges into this equation. [*Nature/human integration*] But that has to be done in other areas. So here we can develop technologies, test it out, in well hopefully smooth conditions and then bring it on to whatever practical project we have. [[redacted] ***as an ad-hoc "scientific" laboratory to develop science and technologies in more or less controlled conditions?? Convergence of natural and social (see creation of fiber-optic internet above) aspects. See also (Bowker 1994), Latour*** *(1993), etc. My note: If the space is so important, does ANT e.g. properly account for it?*]

CREATING THE LAB – [BOOTSTRAPPING]

create the lab.

Me: But are you planning to develop operations in that area?

S: That is being discussed and there is of course one reason why we are doing this, it is to gather background data for potential future operations. But this depends on a lot of things. It's very much depending on the elections in Norway… [*Oil and gas* ***companies*** *not only creati* *networks/infrastructures but also part of a larger networks/infrastructures with social, ethic*

II|IB

Politics in the II that oil and gas is part of.

Figure 14. Snapshot of a manually coded interview transcript.

To summarize, theoretical themes might come to the foreground in three ways:

1) A theory I already know can emerge as I cluster the codes;
2) As I read a book or a paper I can be struck by a theme that reminds me of my case, so I go back to the data and look for it;
3) As I am discussing things with others, it might be that it emerges from the dialogue. This is for instance what happened as I identified the "Creating the laboratory" theme (Paper 4). When discussing a transcript with my supervisors, one was suddenly reminded of Latour's work, in particular (Latour and Woolgar 1986). I then went back through all my data to look for this construct.

Table 5 includes an excerpt of the interpretive template from Paper 4 that is the result of steps 1-7 listed above. Originally interested in instances of infrastructural inversion, we coded the field notes and identified a set of concerns expressed by the interviewees. We thus clustered the concepts into constructs that were based on relevant theoretical themes (e.g. "Bootstrapping").

Table 5. Example of interpretive template (Paper 4)

Construct	Concerns	Excepts
Bootstrapping	Sensor configuration	“*We had to find something with some sort of living coral reef that was flat enough, and we went through a lot of nicer reefs (…) But we had to move away from them because we couldn’t find any place for the camera*.” (Environmental advisor 3) “*Another problem about [Venus] is that the fish experts… lack experience with reading the [acoustic] sensors from [the sea] floor.”* (Environmental advisor 4)
	Granularity vs. scope	“*[T]he [ocean observatory] or the sensors—they can’t see if it’s larvae.*” (Environmental advisor 4) “*A big fish or a big swimming bladder will return a bigger signal than a smaller one (…)Perhaps that’s why we have come up with species with a swimming bladder in this project.*” (Environmental advisor 4)

It is important to note that data analysis never concludes in one round. As there is a constant dialogue between data and theory, it has rather been a process. As Klein and Myers’ (1999) fundamental principle of the hermeneutic circle suggests, the relationship between the parts and the whole is not fixed. The unit of analysis might indeed vary for different purposes. As my understanding of the case evolved, the same data were analyzed in different moments sometimes with very different lenses, such as those for writing different papers. Data analysis was particularly intense before and during the phases of article writing. For example, the data about the deployment of a subsea observatory in the vicinity of a coral reef in north Norway were analyzed first as an instance of the work required to bootstrap the infrastructure (Paper 4). Later the same dataset also emerged as an instance of the infrastructural work to construct environmental risk representations (Paper 5).

In general, the data analysis work was iterative, encompassing several hermeneutic circles. The link between theory and data was constantly formed and re-formed through coding, triangulation, literature analysis, and discussion with other researchers or actors in the field. Sometimes additional rounds of data analysis were triggered by further data collection. If I was uncertain about how to make sense of my data, I would contact the relevant informants to ask for clarification. It would occasionally happen that the new information would trigger a new understanding of some datasets.

The generalizations that resulted from the data analysis process produced the elaboration of concepts such as infrastructuring (Paper 4 and 6), nested materiality (Paper 5), and infrastructural inversion and bootstrapping and enactment (Paper 4). In other cases, we also aimed to draw specific implications for design (Paper 3 (Mikalsen et al. 2014)) or a better insight into the pragmatic management of collaborative projects (Paper 1 (Parmiggiani and Hepsø 2013)).

5 Results

Enclosed in this thesis are the following seven papers:

Paper 1. Parmiggiani, Elena; Hepsø, Vidar. (2013) *Pragmatic Information Management for Environmental Monitoring in Oil and Gas*. In Proceedings of the 21st European Conference on Information Systems (ECIS), Utrecht, The Netherlands, June 5-8, 2013, Paper 65

Paper 2. Parmiggiani, Elena; Mikalsen, Marius (2013). *The Facets of Sociomateriality: A Systematic Mapping of Emerging Concepts and Definitions*. In Nordic Contributions in IS Research Lecture Notes in Business Information Processing, M. Aanestad and T. Bratteteig (eds.), Springer Berlin Heidelberg, pp. 87–103

Paper 3. Mikalsen, Marius; Parmiggiani, Elena; Hepsø, Vidar (2014). *Sociomaterial Capabilities in Integrated Oil and Gas Operations - Implications for Design.* In Proceedings of the 22nd European Conference on Information Systems (ECIS), Tel Aviv, Israel, June 9-11, 2014, Track 20, Paper 3

Paper 8. Parmiggiani, Elena; Monteiro, Eric; Hepsø, Vidar (2015). *The Digital Coral: Infrastructuring Environmental Monitoring*. Submitted to Computer Supported Cooperative Work (CSCW) (under review after first round revisions)

Paper 4. Parmiggiani, Elena; Monteiro, Eric (2015). *The Nested Materiality of Environmental Monitoring*. Submitted to the Scandinavian Journal of Information Systems (under review after second round revisions)

Paper 5. Parmiggiani, Elena; Monteiro, Eric (2014). *A Measure of 'Environmental Happiness': Infrastructuring Environmental Risk in Offshore Oil and Gas Operations*. Submitted to Science & Technology Studies (under review)

Paper 6. Parmiggiani, Elena; Monteiro, Eric (2015). *Environmental Sustainability: Implications for Green IS.* Submitted to Management of Information Systems Quarterly (under review)

In addition, three papers were published and one was submitted during the PhD that are not included in this thesis:

A. Parmiggiani, Elena (2012). *Supporting environmental monitoring in Integrated Operations: a preliminary study.* In The 35th Information Systems Research Seminar in Scandinavia (IRIS 2012): Sigtuna, Sweden, 17-20 August 2012

B. Parmiggiani, Elena (2014). *Of Corals and Web Portals: Towards a Digital Representation of Risk for the Cold-Water Corals in the Oil and Gas Sector*. COOP 2014 - Proceedings of the 11th International Conference on the Design of Cooperative Systems, Nice, France 27-30 May, 2014

C. Parmiggiani, Elena; Monteiro, Eric (2015). *Digitized coral reefs*. Submitted to the digitalSTS Handbook, J. Vertesi, et al. (eds.), http://digitalsts.net/

The data and results presented in Paper A represent a preliminary study and became part of Paper 1. The data and results of Paper B are already included in Paper 4). Paper C is instead only partly overlapping with Papers 4 and 6.

The papers were written throughout the duration of the PhD project but submissions to journals were concentrated in the final year. The papers are listed in chronological order. Even though I strived to retain a uniform overall theoretical basis, they inevitably reflect the evolution of my access to the field site, amount of data collected, and analytical thinking. During my PhD I insisted on collaborating with other members of my research group and the list of co-authors involved in each article mirrors how the cooperative effort has evolved.

As a whole the articles contribute to the goal of this thesis: to make it easier to understand how the initial phases of infrastructure integration unfold in the oil and gas domain with reference to environmental concerns. This aim is phrased as follows:

What characterizes the early dynamics of the integration of an infrastructure for real-time environmental monitoring within the installed base of an oil and gas organization?

The research goal is thus split analytically into the following research questions:

1) How does real-time environmental monitoring emerge as an infrastructure?
2) How is this process mirrored by a changed representation of environmental risk perception in an oil and gas context?
3) How can such a long-term and large-scale problem be addressed at the methodological level?

Table 6 summarizes the research questions that are answered in each paper and in the thesis as a whole.

Table 6. List of papers and the research questions they answer. Dots are bracketed if the question is only partially addressed in the paper. Under each label is the field of contribution (IS; CSCW; STS).

	RQ1 Information infrastructure	**RQ2** Environmental risk	**RQ3** Infrastructural inversion
Paper 1 [IS]	●		
Paper 2 [IS]			(●)
Paper 3 [IS]	●		
Paper 4 [CSCW]	●	●	
Paper 5 [IS]	●		
Paper 6 [STS]	●	●	
Paper 7 [IS]	●	●	
Thesis	●	●	●

Paper 1 was written about seven months after the beginning of the fieldwork. It analytically identifies the challenges related to the implementation of semantic web-based solutions in NorthOil. Although it mirrors the strong focus in the EnviroTime project on semantic technologies which was later abandoned, the paper refers to an information infrastructure theoretical rationale and draws implications for the study of integration efforts within infrastructures. Paper 2 is theoretical and aims to clarify the status of the research stream on sociomateriality by identifying its core facets for the IS field. This paper is a preamble to Paper 3 which extends the findings with two empirical cases and draws implications for the design of integrated systems in the oil and gas sector.

Papers 4-7 are journal papers and represent a comprehensive effort to connect my PhD work to the literature in CSCW (Paper 4), IS (Paper 5 and 7), and STS (Paper 6). They are all empirically grounded. Paper 5 is motivated by the prior work in Papers 2 and 3 and contributes to the sociomateriality literature by unpacking the role of material elements within infrastructures. Papers 4, 6, and 7 explicitly elaborate the concept of infrastructuring that is core to this thesis. Paper 4 does so by investigating the constant articulation work enacted in infrastructures to balance discrepant targets. This paper is the extended version of paper B. Paper 6 unpacks the notion of environmental risk and focuses specifically on how the infrastructuring efforts also actively change the perception of environmental risk. Paper 7 elaborates on the relevance of an infrastructuring perspective for the field of Green IS.

To conclude, Papers 4 and 6 contain ideas for addressing empirical studies of information infrastructures and operationalizing the concept of infrastructural inversion. Table 7 is a summary of the papers included in the thesis, the field where they were published or submitted, their empirical and theoretical grounding, and their contributions.

Table 7. Overview of empirical and theoretical ground and contribution for each paper included in the thesis.

Paper	Empirical case	Theoretical grounding	Contribution
Paper 1 [IS]	• EnviroTime (first year) • GlobalMapping	• Carlile's framework for knowledge management • Information infrastructures • Equifinality	• Empirically grounded identification of the challenges related to cross-boundary knowledge sharing • Analysis of semantic technologies through an information infrastructure lens • Illustration of how sharing can be performed equifinally by addressing the specificity of the technology
Paper 2 [IS]	--	• Sociomateriality	• Mapping of the concepts and features of the sociomateriality literature • Illustration of the implications for the notion of performativity, for the design of empirical research, and the study of infrastructures
Paper 3 [IS]	• EnviroTime (first year and half) • NorthOil's exploration department routines	• Sociomateriality • Information infrastructures • Capability stack framework • Convergence • Maintenance	• Conceptualization of two sociomaterial capabilities (convergence and maintenance) to contain local/global and rigidity/flexibility tensions in infrastructures • Derivation of seven infrastructure design principles based on the capabilities outlined, in particular to account for the role of materiality and the recursivity of infrastructure
Paper 4 [CSCW]	• EnviroTime (first year and half)	• Information infrastructures	• Generalization of articulation work in infrastructural inversion

	Venus	Articulation work/infrastructural inversion Infrastructuring Bootstrapping Enactment	to address infrastructure evolution over time Analysis of early-stage infrastructuring mechanisms through the concepts of bootstrapping and enactment
Paper 5 [IS]	Venus Peter EnviroTime (environmental value) Environmental monitoring modeling practices	(Socio)materiality Performativity	Empirically grounded study of the performativity of materiality Definition of the concept of nested materiality
Paper 6 [STS]	Venus NorthOil's Online Support Center	Knowledge infrastructures Environmental risk Infrastructuring	Empirically grounded characterization of the infrastructuring mechanisms in the Venus project Discussion of the temporal, spatial, and social dimension of infrastructuring Discussion of phenomena and infrastructure co-construction
Paper 7 [IS]	Venus EnviroTime (only Use Case 1 and 2) Peter	Green IS Performativity Information infrastructure	Review and classification of the Green IS literature. In-depth empirical analysis of Green IS solutions within the oil and gas domain. Proposal for a performative-turn and an infrastructure-turn for the Green IS agenda.

In the following sections I discuss the results of each of the articles listed above in light of the general case framing and theoretical framework adopted in this thesis.

5.1 Paper 1 – Pragmatic Information Management for Environmental Monitoring in Oil and Gas

Empirically, this paper explores the attempt of the EnviroTime project to develop a comprehensive semantic data model to standardize the representation of data related to underwater environmental monitoring (environmental parameters, geographical information, and sensing equipment). The goal was to solve the chronic fragmentation that affects data management not only within operations, but also within marine monitoring practices. We show how the standardization effort emerged as a debate about either adopting top-down representations based on formal Semantic Web vocabularies or a bottom-up Linked Open Data approach based on community-approved vocabularies.

The realization of the data model was conducted as a collaborative effort among members of all companies involved in EnviroTime. We outline the core phases of the development through Carlile's framework (2004) for knowledge management at a boundary between different communities. In so doing, the paper demonstrates that it was practically impossible to overcome syntactic and semantic barriers due to the inherent misalignment of the project partners. Increasing political, business-related, and scientific conflicts came to the surface. The installed base of NorthOil also played an active role in shaping the outcome of the development effort: the initial proposal to adopt highly formal modeling languages was abandoned after the GlobalMapping project was closed for failing to apply the same approach.

Finally, the development of the semantic model was pragmatically turned into a more limited effort based on a Linked Open Data approach without solving the discrepancies and ambiguities among the participants.

Theoretically, this paper aims to avoid a tendency to black-box the technology which characterizes many organization studies (Orlikowski and Scott 2008). It therefore adopts the lens of information infrastructures specifically to conceptualize sematic technologies, which we intend as sociotechnical networks resulting from a process of translation (Latour 2005) involving the users, the developers, and the installed base they seek to represent. This latter point is still underdeveloped in this paper, yet it offers future reference for the *recursive* nature of infrastructure (Jensen and Winthereik 2013), where the installed base is itself shaped by integration efforts.

In sum, the main contribution of this paper to the thesis is two-fold. First, it provides a detailed insight into the unfolding of a cross-community ontology development as a process of integration. Second, it sheds light on one of the fundamental points of my framework, which I labelled *equifinal integration*. It does so by outlining the integration between different environmental datasets and between environmental and operational information as a process that is necessarily conducted by relying on sufficient and temporary levels of shared understanding (cf. Donnellon et al. 1986).

Contribution: I had the main idea as a result of a conversation with Vidar Hepsø. I wrote the paper and Hepsø contributed through discussions, extensive comments, and corrections of the paper.

5.2 Paper 2 – The Facets of Sociomateriality: A Systematic Mapping of Emerging Concepts and Definitions

This paper presents a mapping of the IS literature on sociomateriality and is a basis for future elaborations in Papers 3 and 5. It systematically reviews the literature on this increasingly popular theme and outlines three core facets: mutuality (*what is a sociomaterial assemblage?*); performativity (*how does it perform?*); and multidimensionality (*when and where does it perform?*).

The key notion of sociomateriality is perhaps performativity, aiming to describe the specific enactment of a configuration of reality (Barad 2003). In this view, activities can be understood as pragmatic sociomaterial constructs that are drawn in practice. This perspective is a compass point of this thesis because it enables a theoretical understanding of how the components of a reality evolve and take part in evolving relations with other elements dynamically to provide a situated determinacy to a phenomenon (ibid).

An additional aspect of performativity which is important for this thesis is the way it shapes the data collection methodology adopted by researchers. We recognize that the research design affects how the performativity of a sociomaterial assemblage unfolds. Interestingly, we observe that within the sociomaterial research stream new data types are being retrieved in addition to 'traditional' interviews, observations, and document analysis.

Finally, we note that a sociomaterial perspective could be useful in order to embrace the practical, institutional, and organizational scales and different temporal concerns of information infrastructures.

Contribution: I and Mikalsen had the idea of conducting the literature review. The literature search was split between the two authors. I conducted most of the literature analysis and wrote sections 3, 4, and 5. Mikalsen contributed by writing sections 1 and 2 and through discussions and corrections.

5.3 Paper 3 – Sociomaterial Capabilities in Integrated Oil and Gas Operations: Implications for Design

Empirically, this paper investigates integration in infrastructures by looking at the Integrated Operations initiative in NorthOil (see also Chapter 3). It does so by focusing on two different case studies conducted in NorthOil by myself and my colleague: environmental monitoring and subsurface exploration. Building on the findings of Paper 2, this paper bridges the theory on information infrastructures and organization studies literature (in particular the capability stack by Henderson et al. (2013)) to show how 'Operations' are 'Integrated' in practice.

We identify two empirically observed capabilities: convergence (cf. Bowker and Star 1999) – to contain the tensions between global standardization requirements with the local and fragmented installed base – and maintenance (cf. Star and Strauss 1999) – the often neglected work to keep practices and systems flexible for the unexpected.

We propose seven practical information infrastructure design principle based on the capabilities observed. Even if not stated explicitly in the paper, the capabilities are an attempt to empirically delineate and address the recursivity of infrastructure. They demonstrate how tensions between different scales emerge in practice and how they are met pragmatically in practice. In particular, we show (see, e.g., Design Principle Two) how, in this process, the installed base not only provides a resource for evolution, but that, when this happens, it is itself part of the evolution.

Finally, this paper extends the literature on sociomateriality by noting what is more extensively developed in Paper 5: information infrastructure design should account for the multiple levels of materiality that are folded into each other in reality (see Design Principle Three). Sociomaterial design must therefore encompass not only the human/ICT interface, but rather the interfaces between humans, the sensing and representational technologies, and the natural elements being monitored.

Contribution: Mikalsen had the main idea for this paper as a consequence of our collaboration. Empirical data were made equally available by me and Mikalsen. I participated in the analysis and wrote the majority of sections 2 and 3.1. I also wrote parts of section 4. Other sections were written by Mikalsen. I proposed the elaboration of the concept of convergence, whereas Mikalsen proposed that of maintenance. I also contributed to the discussions with Mikalsen and Hepsø. Hepsø contributed to the elaboration of the empirical data and input to the context. Hepsø also provided feedback and corrections.

5.4 Paper 4 – The Digital Coral: Infrastructuring Environmental Monitoring

This paper addresses the initial stages of infrastructure integration. It does so through the concept of infrastructuring, which we define here as the co-evolution of infrastructures and work practices. In particular, the paper contributes to infrastructure studies and to the CSCW literature by clarifying the dynamics of infrastructuring on the empirical and theoretical level.

Empirically, we detail how the Venus project first and the EnviroTime project later began to constitute an information infrastructure for real-time environmental monitoring in NorthOil.

Theoretically, we adopt the lens of infrastructural inversion (Bowker 1994; Bowker and Star 1999) and propose it in order to look at the constitutive role of articulation work over time. In so doing, we relate our theoretical underpinning to the CSCW literature.

We identify two partly overlapping processes of infrastructural inversion from the literature (bootstrapping and enactment) and we instantiate them through a rich empirical characterization.

Bootstrapping mechanisms are meant to locally explore the feasibility of the devices and methods to set up the new infrastructure. We discuss one dimension of bootstrapping in particular, viz. trustworthiness building. Given the political relevance of activities related to oil and gas (see also Chapter 3), the bootstrapping phase of infrastructuring is characterized by an effort to ensure the legitimization of NorthOil's environmental initiatives in the eyes of internal and external stakeholders. Trustworthiness building is important with reference to one of the tenets of this thesis: the construction of a perception of environmental risk (see also Paper 6). Even if not discussed in depth in the paper, trustworthiness is enacted on at least two levels: by quantifying results in particular ways and embedding them in the decision making processes and by leveraging the rhetoric appeal of specific environmental resources (corals above all). These two aspects exemplify two points of the theoretical framework presented in Chapter 2: first, that environmental risk emerges from the infrastructure that quantifies it; and secondly, that materiality has socio-political implications.

Enactment mechanisms increasingly characterize subsequent stages of the infrastructure evolution and present stronger degrees of integration of the new approaches with the installed base of NorthOil and the oil and gas sector. As part of the work of enactment, we front-stage the entwining of scientific work and articulation work in environmental risk assessment (a tenet of infrastructural inversion, see Chapter 4). Once again, this suggests that environmental risk emerges as an epistemic problem. Its perception co-evolves with the infrastructure that measures it: as the infrastructure is increasingly embedded into oil and gas daily operations, new knowledge is generated, which in turn allows new questions to be asked and new methods to be developed (e.g., repurposing a sediment trap into a real-time tool).

Contribution: I had the main idea for the paper and proposed elaborating the notion of infrastructuring through bootstrapping and enactment. Monteiro had the idea of submitting the paper to a CSCW outlet. I had the main responsibility for the data collection and the data analysis which was aided by the frequent discussions with Monteiro and Hepsø. I wrote most of the paper, Monteiro wrote the majority of sections 1 and 2 and polished and corrected the article. Hepsø also contributed by providing corrections, feedback, and by writing subsections in earlier versions of the manuscript.

5.5 Paper 5 – The Nested Materiality of Environmental Monitoring

This paper looks into the production of facts in subsea environmental monitoring in remote areas. In general, the article focuses on one facet of infrastructural inversion by unraveling the move from controversial claims (possibility of operating in environmentally sensible areas) to the establishment of a knowledge base about marine ecosystems. We therefore focus on the how facts are materialized with the support of an infrastructure-in-the-making (cf. Edwards 2010).

Empirically, we draw upon the particular moments in NorthOil's projects that were crucial to determining what aspects of the marine environment to select (e.g., corals, fish); how to measure them (e.g., how to position the sensors); and how to visualize them (e.g., level of granularity).

Theoretically, we draw on the literature on sociomateriality and particularly on the concept of performativity (Barad 2003; Jones 2014) to unearth the way that interacting aspects of NorthOil's infrastructure-in-the-making shape the way facts are produced. We leverage the lens of information infrastructure (Jensen and Winthereik 2013; Monteiro et al. 2013) to describe how facts emerge from a distributed and interconnected network of tools, devices, and human experts, rather than from the interface between humans and single artifacts or sensing devices alone. In this way, we open the black box of the material circumstances that generate the capacity for environmental monitoring.

As a major contribution to the literature we propose the notion of nested materiality that characterizes how facts emerge from the recursive entanglement of nature, the distributed infrastructure technologies, and the experience of human experts.

In sum, nested materiality is meant to demonstrate the performativity of subsea environmental monitoring as distributed and interconnected – as opposed to focusing on the role of single artifacts – and as constantly interacting – as opposed to a black-boxed approach to technology.

Contribution: I had the main idea for the first version of the paper as a result of frequent discussions with Monteiro. The initial version however changed as part of the revision process and the current version is based on an idea by Monteiro. I wrote most of the paper and Monteiro wrote sections 1 and 2 and provided feedback. He also corrected and polished the paper. I had the main responsibility for data collection; data analysis was mostly conducted jointly by the two authors.

5.6 Paper 6 – A Measure of 'Environmental Happiness': Infrastructuring Environmental Risk in Offshore Oil and Gas Operations

This paper investigates the quantification of uncertainty into facts about the environmental impact of oil and gas routine operations.

Empirically we look into the infrastructuring mechanisms of NorthOil to establish a knowledge base of the Venus subsea environment against which to assess the impact of potential future oil and gas operations. We demonstrate three infrastructuring mechanisms: the repurposing of acoustic sensors to detect marine biomass from the seafloor; the validation of the local measurement when there are no baselines; and the abstraction of the sensor-based datasets into risk representations such as the environmental value and the risk matrix. In the case of validation, we particularly followed the way NorthOil took inspiration from the established mechanisms in use at the company's Online Support Center (OSC) to validate drilling-related data. The OSC was contacted as part of the data governance and stakeholder management work package within the EnviroTime project – in the phase when EnviroTime intersected with the Venus project.

On the theoretical level, given the strong element of knowledge building involved in the Venus project, we explain NorthOil's infrastructure for real-time environmental monitoring as a knowledge infrastructure (Edwards et al. 2013). We leverage the literature on the sociology of risk and on marine policy (as discussed in Chapter 2) to explain that NorthOil is not only infrastructuring new environmental monitoring solutions, but also new representations of oil and gas-related environmental risk. In so doing, we demonstrate empirically how the phenomena and the knowledge infrastructure are co-constructed. We do so by detailing the three mechanisms outlined above and by discussing three facets of NorthOil's infrastructuring approaches in the dimensions of time, space, and trust.

In terms of space, our key finding is that the more infrastructuring approaches attempt to be global, the more they are rooted in the local and situated context. In terms of time, we observe that NorthOil's infrastructuring mechanisms are an effort to balance contrasting time scales (e.g., minutes for well drilling, centuries for submarine ecosystems). These mismatching perspectives must be frozen into representations of environmental risk that make sense to heterogeneous audiences, as is the case of the risk matrix. NorthOil's approach to turning environmental monitoring into a real-time task is reshuffling the time lag that has given birth to the current approaches to environmental risk assessment in the oil and gas industry. Turning environmental risk into a real-time, live matter (e.g., the Venus web portal) implies a reconfiguration of the material arrangements in the monitoring infrastructure that is generative of new perspectives on environmental risk. Finally, we discuss how NorthOil is putting into practice a series of mechanisms of social infrastructuring (Bowker 1994), ultimately targeted at creating a relationship of mutual trust with the authorities, the general public, and the contractors.

In sum, through our analysis we emphasize that environmental risk has not only a social and political nature (Beck 1992; Douglas 1992; Jasanoff 1999), but is also dependent on a process of material enactment within the infrastructure for environmental risk assessment (see also the concept of nested materiality, Paper 5) that is characterized by a continuous oscillation between different temporal and spatial dimensions. Balance in ensured by a careful work of building trust with external stakeholders around NorthOil's means, rather than ends, for real-time environmental monitoring. This finding invites researchers to address the way that environmental risk is defined and shaped by the infrastructure that makes it possible.

Contribution: I had the main idea for the paper and wrote most of it. Monteiro wrote section 7 and contributed to structuring the paper. He also participated in discussions and provided corrections and feedback. I had also the main responsibility for the data collection and analysis.

5.7 Paper 7 – Environmental Sustainability in Oil and Gas Operations: Implications for Green IS

This paper is a programmatic article that argues in favor of an infrastructure-turn for the Green IS agenda.

Based on a systematic literature review of the Green IS literature we identify two major shortcomings of this nascent yet immature research stream: the difficulty of incorporating the most recent conceptualizations of the performative interplay of technology in organizations (cf. Orlikowski and Scott 2008) and an inability to shift the perspective "from artefacts to infrastructures" (cf. Monteiro et al. 2013) to understand the ICT-related challenges of environmental sustainability.

Empirically, we sampled three vignettes from the case study presented in this thesis to showcase the way that environmental monitoring is conducted at three points of the lifecycle of an oil well: Venus (planning), Peter (production), and EnviroTime (drilling). We adopt these scenarios to demonstrate that environmental sustainability is, first of all, performative: environmental risk assessment practices do not provide absolute truth about nature, but they are meant to turn nature into relevant and meaningful facts for various professional audiences to allow them to answer pragmatic questions about the sustainability of their activities. We thus describe how, in this process, aspects of the subsea environment are selected, for example, by embedding implicit assumptions about what deserves the status of 'relevant' environmental resources (e.g., the corals, but not the marine mammals). These features are then abstracted into seemingly simple risk re-presentations such as the coral risk matrix. As we also show in Paper 6, the more these re-presentations of risk are meant to be global and understandable everywhere, the more they are embedded in the local setting. For instance, to interpret a coral risk matrix an environmental expert needs situated knowledge of the area where the measurements fed into the matrix were taken.

Second, we elaborate on our argument that the machinery to ensure environmental sustainability must be studied as an infrastructure. By definition, information infrastructure balances situated needs while also stretching across temporal and geographical boundaries (Star and Ruhleder 1996). We show how NorthOil's environmental monitoring systems are interconnected and interactive. These aspects are the reason why the information infrastructure lens is useful for unpacking the unfolding of environmental monitoring: NorthOil's tools, sensors, and systems are kept interconnected in time and across geographical areas, yet they interact successfully on the pragmatic level in different locations for specific purposes.

The article closes by providing some reflections around the political meanings associated with the Green IS agenda. According to our analysis, *what* fact about the environment is known is tied to *how* the fact is known (cf. Barad 2003; Østerlie et al. 2012). NorthOil's attempts to make the environmental monitoring machinery real-time are interesting to study because they are reshuffling *how* the fact is known. Associated with this reconfiguration is a demonstration that controversy is often a necessary part of fact construction. In terms of this thesis, I will say that controversy is a constituent part of infrastructuring (see also next chapter).

Contribution: The idea for looking into the Green IS field was the result of frequent discussions with Monteiro. I conducted the systematic literature review and wrote most of the paper. Monteiro wrote section 1 and participated through extensive discussions and feedback, in particular on the structure and of sections 6 and 7. I had the main responsibility for the data collection and analysis.

6 Implications

6.1 Contributions to theory

Integration by infrastructuring is used to describe NorthOil's efforts to develop or adapt solutions to address a problem that is under constant definition such as subsea environmental risk. In this process, the professional disciplines and the scientific knowledge involved are being (re-)defined together with the infrastructure.

In the next sections I discuss how this thesis answers the research questions presented in Chapter 1 through the theoretical framework proposed in Chapter 2.

6.1.1 The emergence of real-time environmental monitoring as an infrastructure

On the recursivity of infrastructure. NorthOil's real-time environmental monitoring infrastructure is both global and local. Large-scale projects with macro political and economic intents such as EnviroTime are constantly in dialogue with very situated efforts such as the Peter and the Venus initiatives. The more NorthOil's infrastructure goes global, the more it becomes local (Papers 4 and 6; Almklov et al. 2014). The consequence of this observation is a key message for scholarly accounts of infrastructure evolution as a process driven either by top-down managerial decisions or by bottom-up initiatives. Infrastructure is necessarily always both. It must hinge on both high-level support (see the funds to the Venus project provided by NorthOil's management) and on more under-the-radar initiatives (see the decision to develop the Venus web portal). These directions depend on each other. Based on NorthOil's case, it would be naïve to tell a story of successful infrastructure integration driven by few heroic actors or by illuminated managers. In line with the principles of interpretive research (Klein and Myers 1999) and as recognized by a perspective grounded on sociomateriality (Orlikowski and Scott 2008), infrastructure evolution is a result of everyday practice which is constantly "configured and reconfigured by multiple meanings and materialities that are fused together in the engineer's work." (ibid, p. 469) Drawing upon a recursive understanding of infrastructure's complexity, therefore, this invites researchers to investigate the way that actors are constantly instantiating their own scales and evolving relations (Jensen 2007; cf. Callon and Latour 1981). Scales and perspectives are always fluid and negotiable, therefore infrastructure evolution can be described in terms of how scales and perspectives are deployed in multiple practical and material circumstances and how they intertwine and temporarily stabilize (Jensen 2007). These interactions have political consequences in terms of a reconfiguration of authority and power (Callon and Latour 1981). It is therefore important, from a scholarly point of view, to spell out how these consequences emerge empirically from the interplay between infrastructure and its phenomena of interest. In the case of NorthOil, the phenomenon is largely undefined: it only exists in terms of the (limited) knowledge about it (Beck 1992). NorthOil's aim to build a sound 'knowledge base' about marine ecosystems recognizes that knowledge has a strong political significance and, consequently, that risk management implies a redistribution of power and authority (ibid). I will discuss the co-evolution between risk and infrastructure in more detail in the next section.

On equifinality and the vagueness of infrastructure. Equifinality front-stages the temporal dimension of NorthOil's infrastructuring approaches: they are always both short and long term. The crucial nature of an equifinal approach is evident in NorthOil's case where the integration effort has not yet stabilized (it is indeed an infrastructure-in-the-making). Future possibilities are still open, thus making not only the spatial dimension but also the temporal unfolding very visible. In NorthOil's case, thus, the vagueness of the future of the infrastructure is socially and politically strategic to evolve in the face of uncertainty. What I am saying by stressing this point is not that NorthOil, as an oil and gas company, is being hypocritical towards the political landscape and the environmental organizations, but rather, that a strategy that a QCB environmental expert called "*[to] have the infrastructure ready,*" was recognized in other settings such as AIDS/HIV research where the same strategy was described with these words: "*'…we were ready to handle just about any cause, as long as it wasn't aliens'*." (Ribes and Polk 2015, p. 10) Empirically, we have confirmation that the vagueness of information infrastructures is a condition for their workability (Jensen and Winthereik 2013). What this point teaches us on a theoretical level is that infrastructure can exist without being thoroughly defined: "Sometimes vague definitions are helpful."[18] The same approach is behind Bowker's (1994) concept of bootstrapping: to better understand the unfolding of the early stages of infrastructure evolution, we must be ready to see it as a heuristic strategy where the local and the global, the long term and the short term are not pre-given but are often pragmatically performed in practice.

On the role of the installed base. Thinking of infrastructures as empirically and theoretically vague moves their recursivity to the foreground: the non-linearity of the infrastructuring process constantly opens new gaps (Jensen and Winthereik 2013; cf. Hanseth and Lyytinen 2010). NorthOil's projects showcase one particular aspect of recursivity: the installed base is also part of the infrastructuring cycle[19]. The infrastructure literature, however, has generally overlooked the role of the installed base as something that affects infrastructure development but remains relatively stable (Ciborra 2000; as referred to by Jensen and Winthereik 2013). Assuming that there is a

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[18] I thank Brit Ross Winthereik for this comment; this point was also inspired by a comment by Eric Monteiro in a plenary session at the Innovation in Information Infrastructures workshop at the University of Oslo in October 2014.

[19] I thank Brit Ross Winthereik for discussing this point with me.

distinction between infrastructure and installed base, some scholars have, for example, begun to problematize the relationship with the installed base and its 'inertia'. (Karasti 2014; Monteiro and Hanseth 1996; Star and Ruhleder 1994) When the EnviroTime project began, it was assumed that the GlobalMapping project would have delivered a general ontology of domain and production data in NorthOil, and even more, that it would have proven that a general ontology of that sort was possible. When EnviroTime was well underway, however, GlobalMapping was closed, triggering a reconfiguration process in the foundations of EnviroTime. This demonstrates that the installed base not only hinders infrastructure evolution through its inertia; but it instead has an unstable role that also evolves with the infrastructure, for instance with remarkable changes to the IT foundations. That was also the case when EnviroTime embraced the datasets from the Venus project. The participants of EnviroTime initially envisioned the real-time environmental monitoring infrastructure as able to handle data that were more detailed than those collected in Venus. The installed base of the EnviroTime infrastructure had to be, however, rearranged to face a reality where the only monitorable fish were those with a swim bladder, and fish eggs and larvae were not well visible, so solution to incorporate eggs and larvae spreading models had to be sought.

On the role of materiality. This intrinsic uncertainty is embraced by a performative understanding of infrastructure evolution. A vague definition of infrastructure makes it clear that infrastructural relations and boundaries are not fixed or pre-given, but emerge from practice (Orlikowski and Scott 2008). This is exactly why materiality (or the process of enacting material reality) deserves more attention in infrastructure research: spelling out the role of materiality brings two benefits. First, it helps to understand why some infrastructuring approaches succeed while others fail – again, by overcoming dichotomist accounts of knowledgeable managers versus solitary employees. Second, understanding the folding of materiality in daily practice helps us to unpack the simultaneously local and global nature of infrastructure (Almklov et al. 2014; Star and Ruhleder 1996). Appel (2012) has vividly illustrated how the specificities of the local operational settings of oil and gas industry become visible as the industry tries to modularize its operations throughout the world. In sociomaterial terms, disentanglement implies entanglement. NorthOil faced the same problem in Brazil and in Venus: the more it tried to modularize its environmental monitoring approach, the more it materially entangled with the local communities. While the two ocean observatories were initially as similar as possible, the materiality of the settings molded the infrastructure very differently. In Venus the company needed a fiber-optic connection, so it financed a connection for the onshore community. In so doing, it became locally very visible and infrastructural to the local community. In Brazil on the other hand, the Peter project had to give up on real-time data transfer because the local fishermen did not respect the borders of the oil installation and used the data-transfer buoy to anchor their boats.

Implications for Green IS

Although I have largely referred to environmental risk management in this thesis, the themes discussed in the previous section are also relevant to environmental sustainability in general. In particular, they have direct implications for the nascent but immature research stream on Green IS (Paper 7). Despite Watson et al.'s (2008) call for an approach to environmental sustainability as more than the relationship between artifacts and end users, the field has so far privileged confined studies of the impact of specific artifacts or on the almost dichotomist relationship between artifacts and users. Even when the intention is to adopt a wider scope (Jenkin et al. 2011), the analytical lens is on circumscribed artifacts or practices (e.g., reducing the hours spent travelling, videoconferencing systems) rather than on the complex whole that is formed by the interrelationship between these elements. I maintain that my analysis is relevant for Green IS research on the theoretical and on the empirical level.

The performativity of Green IS. Theoretically, Green IS research should be addressed as a performative accomplishment: we must attend to the daily practice of enacting environmental sustainability in organizational realities. NorthOil's offshore environmental monitoring practices are a vivid example of performativity: they enact specific materializations of the subsea world (cf. Orlikowski and Scott 2015a). They do so relationally because they constantly draw and re-draw connections between natural elements, sensing devices, modeling tools, heterogeneous actors, norms, and work processes. This lens invites us to look at environmental sustainability as the result of a process of practical enactment where its boundaries are drawn temporarily to determine a phenomenon (Barad 2003) – e.g., using the environmental value for assessing sustainable operations in Venus. On the empirical level, the message for Green IS research is to approach environmental sustainability by relying on more in-depth, longitudinal empirical studies. Without an empirical understanding of the specificities of an industrial setting, it is, I maintain, hard to draw research results that can influence industry standards or government policy (Watson et al. 2012). If we consider NorthOil's case, the approach to environmentally sustainable operations emerged differently in Brazil and in Norway. This means that a better understanding of the entanglement with the local settings (cf. Appel 2012) is also important to design and implement information systems for environmental sustainability.

Towards an infrastructure lens to Green IS. A sociomateriality-grounded approach to performativity arguably has shortcomings in analyzing the temporal and spatial unfolding of complex organizational arrangements. I believe that we should look at the latter as information infrastructures, and thus investigate aspects of interconnectedness, distribution, and interaction (see also Paper 5). In particular, infrastructuring is useful as a unit of analysis in this respect because it helps researchers to unearth emerging infrastructural relations over time and multiple contexts that would otherwise be ignored or taken for granted (Monteiro et al. 2013; Williams and Pollock 2012).

In sum, from a performative point of view we are better equipped to disclose how environmental sustainability co-evolves with the monitoring infrastructures.

6.1.2 The co-evolution of the infrastructure and environmental risk perception

It might be that NorthOil fails to stabilize its information infrastructure for real-time environmental monitoring. Projects like EnviroTime, Venus, and Peter are nevertheless performative in terms of triggering a changed perception of environmental risk for different audiences (e.g., the public accessing the Venus web portal, the fishermen, and the drilling engineers)[20]. This statement is grounded in the idea that infrastructure and the perception of phenomena co-evolve (Bowker 2000; Paper 6). To extend Edward's (2010) words, infrastructure and facts support each other. In this sense, then, I suggest that environmental risk is infrastructural in nature. This point front-stages a bidirectional connection between infrastructure integration efforts and risk definition.

Risk conceptions evolve because infrastructure integration efforts convey new perceptions of risk. In so doing, they are performative on at least three levels. An example is the digitalization process of environmental monitoring that underlies the Venus project. An apparently simple web portal displaying the updated status of the water column surrounding a coral reef enacts the subsea environment as something that is close, full of light, and quickly accessible. With newspaper articles presenting the portal as "more popular than the Disney Channel," the environment is almost turned into a cartoon with lovely animals.

The infrastructuring mechanisms put in practice by NorthOil to promote the portal (e.g., the visit to the fishermen community, Paper 6) are performative of the idea that the company would be able to handle – or even prevent – possible damage to the environment caused by its operations. Interestingly, as noted in Chapter 3, the same infrastructuring mechanisms around the Venus web portal are used to convey the opposite idea for the IMR: such a beautiful environment should not be harmed by oil and gas activities.

Finally, infrastructuring mechanisms are performative of the audiences for whom environmental risk during oil and gas operations is relevant. In the case of NorthOil, infrastructuring mechanisms speak to the other large-scale industry in Norway – fisheries – by, for example, presenting them as the results of the Venus project or by assessing risk for the fish species that are commercially relevant for them (cod and

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[20] I thank Marisa Cohn for discussing this point with me.

herring). These mechanisms also speak to the IMR, also entwined in NorthOil's projects, and to various universities (not the least by allowing my access). A project such as Peter helped to raise the status of environmental risk for the work of oil and gas professionals. It is performative of the idea of environmental risk as very important in terms of technical risk, because its assessment is fundamental for the safety of equipment and consequently human work and life. To the best of my knowledge, however, NorthOil's infrastructuring mechanisms have not spoken to the environmental organizations – not in a visible way, at least. This point is relevant to the infrastructure literature because it demonstrates that the issue of risk definition (in the general sense, not only environmental risk) is crucial for articulating tensions in infrastructure development. In the risk definition process, opinions and experiences are channeled, managed, and not necessarily solved but leveraged. This is one fundamental facet of infrastructural inversion (see also next section): controversies can be maintained, but integration can occur successfully (see also (Barry 2013)).

The other direction of the infrastructure/risk relationship is less visible in the extant literature, but nonetheless, it is a fundamental point for the IS literature on integration. As Appel (2012) demonstrated, the oil industry routines are shaped by conceptions of risk and safety which are tied to shareholder value and actuarial reason. My case study reveals something more, however. If risk is reflexive (Beck 1992), in Latour's (2003) interpretation it generates unexpected networks of heterogeneous elements. Ontological (re-)configurations of risk therefore have consequences that reverberate through the infrastructure. The process of defining risk then has consequences for infrastructure integration. Ribes and Polk (2015) show how research infrastructures can sustain technoscientific flexibility in the face of unexpected change through preparatory and adaptation work on the key resources and services needed to investigate the research objects. NorthOil's projects present a long sequence of articulation efforts to face the ontological change of their objects of interest. As the real-time monitoring infrastructure was beginning to take shape, the scope of the risk assessment became clearer. For instance, when it was decided that cod spawning activities were a risk object, the environmental experts realized that an important indicator of cod spawning is the grunting sound they emit. Given the experience of one of the project partners, ITCorp, with hydrophone data analysis, the project consortium decided to redirect ITCorp's role from a provider of semantic web technologies to the integration of acoustic analytics in the EnviroTime web portal.

More generally, the EnviroTime project generated a faceted notion of risk by discriminating and characterizing different types of risk (environmental risk, technical risk; see Figure 9). The influence of this activity on integration was also explicitly noted by the O&GSolutions project manager. He pointed out that the different types of risk addressed by the project also raised issues of integration with existing infrastructures. This happened as part of EnviroTime Use Case 2 (see Chapter 3). Risk was initially defined as something that involved both the technical equipment and the environment. Once the project incorporated the Venus data – which had nothing to do with technical equipment – risk was turned into risk for the environment only. At the level of integration, this redirected the effort towards incorporating externally developed environmental data analytics tools (e.g., the adaptation of the environmental value by QCB).

The implication of this analysis for IS research that more attention needs to be paid to the temporal unfolding of integration efforts and to the time dimension in general. I say this because the two-way dialogue between the ontology of risk and the infrastructuring mechanisms in NorthOil's case is emerging over time (I use the present continuous form because this process has by no means stabilized). Upon closer scrutiny, we recognized this process reveals competing time scales, generating difficulties in stabilizing a perception of risk (Paper 6). Mismatches occur, for instance, between the time of technology imposed by oil and gas operations (e.g., seconds and minutes) and that of the environment (years, decades, or centuries). Because of this mismatch, infrastructuring mechanisms will always lag behind the environment, ultimately because the environment cannot be 'photographed' in a generic ontology. It can be relationally enacted (or performed), but it will never be an uncontested fact. As the environmental chemist we quote in Paper 6 comments, "*is there such a thing called ecological baseline? Is that possible? Because no environment is constantly… constant over the whole time.*" As I will point out later, this element has implications for the governance of infrastructures.

6.1.3 Between method and theory: An application of infrastructural inversion

The first and obvious answer to the question "*How can such a long-term and large-scale problem be addressed at the methodological level?*" (RQ3) is: through a longitudinal ethnographic study – or at least ethnographically inspired.

Extending the seminal work of Marcus (1995), a range of scholars in IS and organization studies have recently demonstrated that research into infrastructures cannot be exhausted by short-lived, situated studies (see Williams and Pollock 2012). The theme has become very popular within CSCW as well (Schmidt 2011).

Research into infrastructures suffers from the same recursivity problem of its object of interest: the more it is investigated, the more gaps will be found (Jensen and Winthereik 2013), however, I also recognize that research activity is bound to research grants, time constraints (the duration of a PhD project), and is often a solitary endeavor.

I have argued earlier on that this thesis represents an operationalization of infrastructural inversion. It is an attempt to operate a "gestalt switch" (Goffman 1959) to analyze the infrastructure-in-the-making. As I have stressed in Chapters 2 and 4, inversion is like a "pair of glasses" that are worn both by the actors in the field and by the researcher. If that is the case, the work of the researchers and that of the observed actors follow similar paths. As a single researcher, I had to rely on a few "tricks of the trade" (Star 1999) to investigate something that is by definition distributed, historically accumulated, yet still in-the-making. Sharing the inversion glasses of my informants became my main approach to overcoming this issue as I have extensively explained in Chapter 4.

The message for ethnographic studies in IS and CSCW is therefore to gain the most out of the relationship by using the informants as 'scaling tools' (Ribes 2014a). This strategy hides non-trivial complexities, however: if the trajectory of infrastructure development can be seen as a due process (cf. Latour 2004; see section 4.2), then the ethnographic work conducted by the researcher also follows the trajectory of a due process (Hepsø 2009). I will now discuss how this point is relevant in terms of a crucial moment of ethnography, the researcher's access to the key informants who can act as 'scaling tools'.

In general ethnography requires a lot of "backstage" work to access the field, to become known by the actors, and, fundamentally, to be trusted by them. The researcher might also invest considerable time in following the 'wrong actors', informants unable to provide help in terms of scalability. On other occasions, access to a specific set of scaling actors is prevented for unpredictable practical reasons. That was, for instance, the case when my attempts to visit O&GSolutions were ignored. The company undoubtedly had a primary role in heading the consortium of NorthOil's partners in EnviroTime. When it became impossible for me to speak to them, I had to quickly divert my attention to other companies and other informants – something I was able to solve in a matter of a week or two through the efficient suggestions of a NorthOil employee with whom I was in good contact. My personal experience with O&GSolutions has implications for the research design. First, it means that researchers should be prepared to design their research in the face of the unexpected – just as their informants must "have the infrastructure ready" to face ontological change. Second, to accomplish the study of infrastructure regardless of these events, my experience invites researchers to make a significant investment in establishing good social relationships with the informants – an application of social networking mechanisms. In a sense, then, if I am allowed the parallelism, researchers must deploy infrastructuring mechanisms themselves that they will tailor to the specific field site. This applies in particular when the time of ethnography is relatively limited (e.g., only three years in a larger window of infrastructure evolution) and solutions to access information must be found quickly.

Seeing ethnography as a due process is relevant in order to assess the criteria for who should speak on behalf of the non-human elements (e.g., the corals). We encountered this methodological issue when elaborating the concept of nested materiality (Paper 5). The problem of how to grant agency to materiality (and therefore recognize its ability to "speak for itself" (Cecez-Kecmanovic et al. 2014)) is one of the tenets of the sociomateriality discourse, but it builds on long-term discussions in science and technology studies, in particular in actor-network theory – cf. the "Epistemological Chicken" debate in (Pickering 1992), about the opportunity to grant a symmetrical status to humans and non-humans (Callon and Latour 1992). Even if it helps for heuristic reasons to speak of materials as if they had agency, in practice it is the researcher who grants them a voice through the spokespersons she finds. This can happen only inside a sociomaterial entanglement where spokespersons arrange the (imperfect) tools at their disposal and their knowledge and experience to look at what matters to them at any given point in time (Callon and Latour 1992; Latour 1987). Methodologically we must therefore follow the process of construction of the entanglements as a due process and see how the elements which are physically absent (e.g., the corals) are made present through the enrolment of stakeholders' interests and the use of technologies to measure and interpret them (Paper 1).

6.2 Reflections on the governance of infrastructures

The importance of ***not taking the installed base for granted*** (see section 6.1.1) is relevant for the efficient accomplishment of cross-organizational work to operate an oil or natural gas installation. The difficulties encountered in EnviroTime to incorporate technologies from the different partners into the web portal underlines the criticality of integrating work processes and IT systems that involve the oil and gas company and the myriad other operators and contractors of an installation. In the planning phase no assumptions can be made about the compatibility of the systems needed, for example, the formal work processes of companies like NorthOil might not allow external access to their GIS-based map layers. Such problems might introduce delays and consequently financial loss from the non-operational days spent solving integration issues.

The previous points lead us to also underline he fundamental role of infrastructuring approaches in terms of maintaining a relationship of trust about the subsea measurements between the oil and gas company and the contractors and operators (Paper 6). In the case of infrastructures where monitoring capabilities are cardinal to successful operations, ***the monitoring activity should not be taken for granted***. As Yearly (2009) compellingly demonstrated, observations embed a moral and a political vein: "…they depend for their convincingness of a context of mutual trust." (ibid, p. 158) This comment relates to the politics of stakeholder management in infrastructure development and invites managers to invest more in facilitating a context of mutual credibility to increase smoother collaboration with external players.

The ***relational and performative nature of infrastructure*** also has implications. Drawing upon the findings we discuss in Paper 1, if a phenomenon is relationally enacted in practice for the purpose at hand, approaches based on top-down modeling solutions such as general ontologies are doomed to fail. Given this premise, such approaches cannot account for the temporal and spatial fluidity of work in infrastructures. It is too early in NorthOil's initiatives to say whether a Linked Open Data-based approach might be more fruitful, but it is based on a pragmatic way of thinking that best suits local practices and the characteristics of operational sites, which are never identical due to natural, geological, and historical reasons.

More generally, the discourse on modeling solutions is connected to the ***role of standards*** for infrastructure governance. The daily work to develop, stabilize, and incorporate standards on different levels should be recognized as a fundamental part of infrastructuring. In NorthOil's case, standards have come to the fore on several occasions and proved a fundamental backbone for supporting innovation at every level of the infrastructure, such as data transfer, data representation, and work processes. In terms of data representation, the key example is the adoption and adaptation of QCB's Coral Risk Assessment recommended practices (Papers 5 and 7), which enables the linking of large quantities of heterogeneous sensor-based measurements to a universally readable representation such as the risk matrix. The cardinal example of work process formalization is NorthOil's investment in a separate work package in EnviroTime to develop a data governance standard to make sure that environmental monitoring practices become infrastructural to daily oil and gas activities. The insistence on the business relevance of environmental monitoring in the Arctic is mirrored by the detailed and delicate maneuvering to enroll the interest of other disciplines in NorthOil, and in tailoring new formal work processes for them.

My research also has implications in terms of ***accountability***. If we take a sociomaterial approach to its full potential, it implies a non-neutral process because it entails a (re)distribution of resources (Orlikowski and Scott 2008). As Introna and Nissenbaum (2000) demonstrated, web search engines are political in that, in their configuration, they grant or deny access (or make it very difficult) to specific categories of people. But who is accountable for these effects? Is it the developer? Is it the algorithms? Orlikowski and Scott (2015b) show that the agency of the algorithms embedded in TripAdvisor becomes entangled, among other elements, with the crowd of users to enact choices about what to leave explicit or implicit. In the case of organizational infrastructures, this point is relevant because the analysis of material enactments can enable the identification of spokespersons and assessments of who or what configurations are accountable for risks connected to the organizations' activities.

What follows from this point is that my research can provide useful input to ***stakeholder management*** in infrastructure development processes. As we discuss in Paper 6, infrastructuring mechanisms can be carefully tailored to contain unavoidable controversies among contrasting socio-political-economic interests. These contrasts can be leveraged for the purpose of knowledge gathering, such as when an infrastructure project is taking place in a previously unknown setting. This approach requires attention to the relational nature of infrastructure. When new stakeholders have to be enrolled, information must be presented in terms that make sense in their world view – especially when the knowledge creation element is as critical as it is in NorthOil's case. Attention must be paid to the different epistemic practices of each stakeholder group: based on different practices, different interpretations of the world make sense (Jirotka et al. 2005). This point was clear to NorthOil during a workshop arranged to present the results of the Venus web portal development to the fishermen of the Venus area. The fishermen found it difficult at first to recognize the acoustic measurements of the fish population taken from bottom up rather than top down as usual for them. A better acquaintance of the world view of a potential stakeholder is also important because it might reveal that there might be no contrast in the first place. During the Venus project, NorthOil found more common ground with the local fishermen than originally expected. Possibly, both parties have very different agendas with reference to the possible opening of the Venus area to oil and gas activities. Nonetheless, they have *equifinal* interest in acquiring a better knowledge of the natural conditions of the area. What I called integration by infrastructuring thus acknowledges that infrastructure evolution can take place whilst maintaining and possibly exploiting controversies (cf. Barry 2013; Edwards 2010).

7 Concluding remarks

With this thesis I have tried to obtain a better grasp on the blurred intersection of ICT, environmental risk, and the oil and gas industry. My work by no means claims to be exhaustive, yet, it can be considered, I believe, a step towards understanding a theme that is extremely complex on many political, economic, and technological levels.

I have therefore proposed and elaborated on the notion of infrastructuring to characterize the ongoing, ever changing, temporally and spatially unbounded, and reflexive nature of this intersection in the specific background of Norway. In particular, by answering my research questions, I have provided an analysis of infrastructuring on empirical, theoretical, and methodological grounds.

The empirical insight is, in my opinion, one of the strengths of this thesis due to the amount of data collected and to the astonishing level of access from which I benefited in NorthOil and in its partner companies. Three years of research have not been enough, however, to draw a comprehensive trajectory of the Latourian due process (Latour 2004) granted to the subsea environment by NorthOil and its partners' initiatives.

The theoretical framework I presented in Chapter 2 aims to mirror the dynamic intersection I depict empirically and to demonstrate that infrastructuring represents this intersection. In particular, in Figure 4 I sketched the relationship among the theoretical themes and infrastructuring as three partly overlapping bubbles. In so doing, I assumed the themes of environmental risk and information infrastructure to be of similar sizes. In terms of theory, it is evident that, this thesis being centered upon information infrastructure, the corresponding bubble deserves to be a much larger size. In terms of empirical evidence, however, it is still early to predict which of the two bubbles will grow larger. Will environmental concerns drive the infrastructure? Or will the infrastructure frame a new definition of risk? On the grounds of my theoretical framework and empirical analysis, I expect that the answer will be yes to both questions.

Finally, I claimed to make a methodological contribution. To be more precise, it is a meta-level contribution at the boundary between method and theory. The IS literature, influenced by STS and anthropology, is only recently recognizing that the empirical study of infrastructures is not to be underestimated. I hope that my analysis can provide future food for thoughts on the necessity of taking the study of large-scale interconnected information technologies more seriously, and even more important, to dedicate more attention to the ways these arrangements are embedded in specific organizational settings. A bundle of systems will never produce the same dynamics in an oil and gas company and in a humanitarian organization. The social, economic, and political stakes are too different to produce the same outcome. The entanglement of these contextual aspects with the information technologies, the norms, and standards that regulate them, and the people who put them into practice are what constitutes, in my opinion, the information infrastructure.

7.1 Limitations and future work

I recognize that this thesis is affected by some limitations. I believe that the core limitation was time. Even though not every researcher is ‘blessed’ with my prolonged access to an oil and gas company, three years to investigate an infrastructure-in-the-making is a short period. I tried to balance this by conducting a historical reconstruction and by setting the initial date of my case studies in the early 2000s (as explained in section 3.2.2). If we follow the Latourian due process (Latour 2004), I have observed the phase of perplexity, where environmental concerns were voiced; I saw the phase of consultation, represented by NorthOil’s active attempts to get to know the unknown not only by measuring the subsea environment but also by enrolling purposeful allies; I also partly witnessed the establishment of a new hierarchy in the parliament of things, one where some environmental resources and the corresponding expertise have been enrolled and others have been discarded. In the same way, some allies have been enrolled, others have been discarded. I had no time, however, to investigate the institutionalization of a new collective. I cannot draw conclusions at this stage in terms of infrastructure implementation. Hopefully, the implications drawn in the previous chapter will indicate some useful future directions.

Time has also been a limitation in terms of practical data collection. The very first months of my data collection were the same months in which I was learning the Norwegian language. I might have missed the details of some meetings. I also had to hold the first interviews in English. Even if all my informants had a good knowledge of English, I realize that no one can fully express their thoughts outside their mother tongue.

Finally, a limitation of my empirical data collection was the lack of time to negotiate access to O&GSolutions and ITCorp. I tried to balance this flaw by participating is as many meetings as possible with the representatives of those companies and by analyzing the documentation they issued in EnviroTime.

To conclude, the work presented in this thesis leaves room for several streams of future research. I would like to describe here those that are the most interesting in my opinion.

First, with the possibility of investigating the Latourian phase of institutionalization, it would be important for the research agenda on information infrastructures to obtain a better insight into the role of standards for the success of infrastructure. One example is a thorough study of the way technical interoperability standards have been chosen and embedded into the EnviroTime project.

Another relevant path to pursue could be the actual integration of environmental risk analysis systems into the everyday practice of all oil and gas professionals operating a well. Projects such as EnviroTime have paved the way, but its results are only now beginning to be implemented into NorthOil's offshore assets on the NCS.

Finally, a relevant step for infrastructure studies would be to leave NorthOil's perspective and acquire access to one of its project partners, such as QCB, or the IMR. This would enrich the definition of the concept of infrastructuring from a different perspective which is, after all, still focused on the same goal of becoming infrastructural to the process of shaping subsea environmental risk.

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Appendix: The papers and the co-authorship statements

Paper I

Paper 1

Pragmatic Information Management for Environmental Monitoring in Oil and Gas

Parmiggiani, Elena and Hepsø, Vidar

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Pragmatic Information Management For Environmental Monitoring In Oil And Gas

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PRAGMATIC INFORMATION MANAGEMENT FOR ENVIRONMENTAL MONITORING IN OIL AND GAS

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Abstract

The oil and gas industry has an installed base that is characterized by local fragmented approaches for data management. Inside this information infrastructure, real-time monitoring of the subsea environment remains an unexplored arena that demands a cross-disciplinary and cross-organizational data integration layer. Semantic technologies have been proposed in the literature as a possible standardization solution. Their development depends on collaborative processes involving business partners from different industrial domains, thus requiring that an equifinal level of understanding is reached and boundaries of knowledge sharing are overcome.

We describe an ethnographic study from an inter-organizational project in an oil and gas company, where the objective is to develop an integrated solution for real-time subsea environmental monitoring. We identify the challenges that emerge when sharing knowledge at a boundary on a syntactic, semantic, and pragmatic level. (i) The different backgrounds of the organizations involved and (ii) the unresolved issues affecting semantic-based solutions influence the possibility of reaching a shared understanding at a syntactic and semantic level. We open the black box of semantic technologies thanks to an information infrastructure perspective and conclude that collaboration can be carried out on a pragmatic level by addressing the implications of the specific technology.

Keywords: Information infrastructures, Semantic technologies, Environmental monitoring, Knowledge sharing.

1 Introduction

Since the discovery of oil in the North Sea in the late 1960s, Norwegian industries have continued to make technological discoveries that have brought them to the forefront of innovation. Subsea operational facilities are now being installed on the Norwegian Continental Shelf (NCS) for exploration, extraction, and production of oil and natural gas, and these facilities are connected via fiber-optic infrastructures to control centers onshore. A compound element of novelty characterizes this unexplored scenario. Not only are there modern sensors in place to measure various parameters, but the real-time availability of the data opens the door to solutions that were previously unconceivable. However, this process has to fit a reality that is the result of at least 40 years of activities. According to the Norwegian Petroleum Directorate, 70 oil and natural gas fields are in production on the NCS (NPD, 2012). Each of the operational assets connected to them has its own historical background, and its employees have developed diverse local work practices (Rosendahl and Hepsø, 2013). Over the years, massive amounts of heterogeneous information have been accumulating in large databases (or "silos") spread over different systems and different operational fields that can be connected to several wells at the same time. No integrated solution is currently available for standardizing and accessing information across technological, professional, and geographical boundaries (Hepsø et al., 2009). Nevertheless, operators in the sector have learned how to co-exist with this reality and have cultivated daily heuristics and workarounds to cope with it (Monteiro et al., 2012, Østerlie et al., 2012).

The monitoring of the marine environment surrounding the field remains an immature discipline among the many activities performed on an oil and gas asset. Traditionally, environmental samples and data are collected offshore via bi- or triennial campaigns. Physical, chemical, and biological data are shipped to shore, stored, and analyzed, often with a temporal gap of 9-12 months (KLIF, 2011). This methodology may be adequate to report the status of polluted areas and the effects on local fauna. However, it is not suitable to proactively prevent possible environmental damage from current or future activities. A standardization effort is required to achieve a cross-field overview of the status of the marine environment within the information infrastructure of the oil and gas operations. Even when blended into a well-established installed base, real-time environmental monitoring represents a unique opportunity for the industry to abandon the chronically local, silo-based methods of handling information and move towards more global, integrated, and networked practices.

Semantic technologies emerged in computer science as a promising solution to provide standardized and consistent storage and access to real-time multi-sensor data (Gulla, 2009). The development of these technologies is an inter-disciplinary and inter-organizational achievement. In practice, they tend to reproduce the struggle to find a balance between older and newer methods used to manage information that is representative of the information infrastructures they support. On the one side, the oil and gas industry is a conservative and strictly regulated domain that is considered a fertile terrain to apply the standard-based, top-down information modeling solutions to realize architectures for data integration and interoperability (Gulla, 2009, Verhelst et al., 2010). These approaches are endorsed by institutions and non-profit organizations promoting the development of data specifications. On the other side, new tools are being developed, inspired by the Linked Open Data set of best practices (Bizer et al., 2009), to share and reuse community-approved vocabularies that begin to question the role of former approaches.

Understanding how information is transformed into meaningful knowledge is therefore the key when addressing the challenges of standardization processes in situations where the inter-organizational setting does not allow shared communication practices. In this paper, our objective is to provide a better understanding of how collaboration can be organized around *equifinal meanings*, i.e., by relying solely on approximate or sufficient levels of shared understanding (Donnellon et al., 1986). We set the following research question: *How can a collaborative process be performed at an equifinal level?* Our answer highlights the need to include the implications of the technological choices and to adopt an information infrastructure perspective to encompass the absent presences into the culture of an organizational reality.

The remainder of this paper is organized as follows. In section 2, an overview of the theoretical basis underpinning our analysis is presented. In section 3, the method we adopted is described. Section 4 presents the results of the ethnographic study on which our analysis is grounded. The results are further discussed in section 5. Section 6 presents the conclusions and some implications of the study.

2 Towards equifinality in information infrastructures

The availability of real-time environmental data presents an element of novelty in the complex scenario of oil and gas operations. In a recent working article by Carlile and Lakhani (2011), innovation is said to have its “sweet spot” in the tradeoff between the exploitation of older elements and the exploration of newer ones. The innovation cycle is inherently distributed across the relationships between social and technological actors. They form an interconnected socio-technical system, labeled *information infrastructure* by a stream of literature (Monteiro and Hanseth, 1995), to stress the fundamental role of information flows and to acknowledge the importance of understanding the interplay of heterogeneous aspects in design, implementation, and use of technology.

2.1 The top-down/bottom-up tension of standardization

The realization of an information infrastructure in practice is a matter of knowledge management, in that it consists of collecting information from different sources and transforming it into relevant knowledge for diverse audiences. In a complex scenario such as that of an oil and gas company, this process has been depicted as a continuous tension between *top-down* institutional requirements for more global integration and *bottom-up* reliance on information generated locally by heterogeneous disciplines and devices (Hepsø et al., 2009). The addition of a semantic capability to an information infrastructure has emerged in literature as a possible alternative to assigning a unique value to data (Gulla, 2009, Verhelst et al., 2010), thus bringing to the forefront the supporting role of semantic technologies. In practice, semantic capabilities mirror the continuous top-down/bottom-up tension characterizing information infrastructures by enabling different paradigms of knowledge management. One of the features of semantic technologies is the machine-usable content; however, the level of standardization, i.e., *how* information is actually put into the machine is at the heart of the confusion around this definition (Uschold, 2003). Indeed, two distinct and separate camps can be found in the literature. With respect to the first camp, many expectations have arisen around ontologies as a top-down approach to achieve “overall standardization”, and several IT companies have plunged into this new emerging market. For example, the “oil and gas ontology”, based on the ISO 15926 standard, has been used to model oil and gas production plants (Gulla, 2009). Nonetheless, such a methodology is struggling to gain momentum, and experience shows that moving from prototype solutions towards relevant industrial applications is an underestimated problem (Hausenblas, 2009, Hepp, 2008). Top-down semantic information models developed by experts rely on a strong expressive power and predetermined meta-data structures. However it is difficult to make their utility visible to end users who do not directly require them (Hepp, 2008). The fragmented reality of oil and gas information systems and the challenges imposed by the unexplored context of real-time environmental monitoring demand more flexible solutions to account for the local users’ practices and natural characteristics of an operational site. Knowledge about the submarine environment is constantly evolving, and newer generations or combinations of technologies become available on a daily basis. Propositions to integrate the emerging technical and social aspects through bottom-up approaches (e.g., by adopting folksonomies) have been proposed in computer science; see, e.g., Mika (2007). A tradeoff between the power of expressivity and the usability of a semantic data model is necessary in an information infrastructure where the requirements for stricter control must co-exist with the need to find new directions in an open scenario. With respect to the second camp, Linked Open Data have recently come to the fore as a set of best practices for data modeling to connect community-approved vocabularies and datasets (Bizer et al., 2009). They provide the conditions to make (a possibly huge amount of) data available on the Web in a standardized and reusable format, even though to date, few datasets with a clear connection to real-world problems exist (Hausenblas, 2009).

2.2 Negotiation at a boundary

To exit the top-down/bottom-up dichotomy, the formalization of the knowledge flows within an information infrastructure requires an in-depth analysis of the interwoven and dynamic relationships between its elements. Information infrastructures emerge through a socio-technical process of *negotiation* among human and non-human actors. For instance, actor-network theory (ANT) provides a well-known language in the information system research community to delve into complex phenomena and to unwrap an information infrastructure at different levels (Monteiro and Hanseth, 1995). Even if this article relies on an ANT-inspired vocabulary, the argument that it brings forth seeks to avoid a side effect of this approach, i.e., the black-boxing of the technological element in organization studies (Monteiro and Hanseth, 1995, Orlikowski and Scott, 2008). However, the members of an infrastructure have problems that go beyond the technology and encompass economic, political, and organizational factors (Ribes and Finholt, 2009). Later versions of ANT allow for a flexible representation of the mutable interplay between more or less visible actors as well as relationships distributed in time and space (Mol, 2002). The formalization of knowledge is therefore understood to be *dependent on* and *generative of* a set of necessary absent elements brought to presence (Law and Singleton, 2005). To further complicate things, the participants in collaborative practices in the oil and gas industry belong to heterogeneous disciplinary domains and worlds of thought. Nevertheless, they can relate to each other through either material or immaterial artifacts called *boundary objects* (Star and Griesemer, 1989). The difference between the actors' knowledge at a boundary of communication can be divergent, and the consequences of integrating knowledge across domains are not necessarily worth the cost expended. The incompatibility is due to differences in the knowledge regimes, i.e., the combination of artifacts, work practices, and conventions of each actor (Howard-Grenville and Carlile, 2006). A boundary object should be endowed with a common denominator that each community can refer to, but it can play different roles or have "extra meaning" within each separate community (Star and Griesemer, 1989). Objects can be depicted not only as instruments to achieve the successful management of knowledge at a boundary (Carlile, 2004) but also as triggers of contradictions and further negotiation (Nicolini et al., 2012). Their original purpose is enabling a shared level of understanding of the context of action between the communities involved. The exact amount of sharing is difficult to measure, if it occurs at all, but it should at least happen at an *equifinal* level (Donnellon et al., 1986), as quoted by (Berntsen, 2011). *Equifinal* is a term that originated in system theory and is also used in software engineering to describe a situation where a given end state in an open system can be reached by many potential routes. Interpretations might be totally dissimilar but have similar behavioral implications thanks to short-lived and highly situated forms of collaboration and knowledge sharing. Based on the type of knowledge available at a boundary, there are increasing levels of complexity in the communication process: *syntactic* (a common lexicon is sufficient for knowledge transfer); *semantic* (different domains generate interpretive differences); and *pragmatic* (different interests emerge such that finding common knowledge is a political process of negotiation and alignment). Carlile (2004) proposes a well-established theory of practice that consists of three progressively complex capabilities to create enough common ground to unpack the challenges of collaboration in practice: knowledge transfer, translation, and transformation. Innovation in collaborative settings can therefore happen if all three types of capabilities are iteratively developed. It is important to emphasize how for Carlile, translation is only one of the steps to enact collaboration, while in ANT's terminology, it has a more general meaning, i.e., that every process can be decomposed into a translation process.

3 Study context and method

Subsea installations can be integrated with environmental observatories based on existing technologies (e.g., landers equipped with sensor networks, remotely operated vehicles, or floating buoys) to assess on-line the environmental impact of operations. Human presence and direct intervention are not possible on subsea facilities, so sensors are the only source of data available. They might be faulty and differ significantly, e.g., in terms of data representation and accuracy. In addition, the oil and gas industry has no standardized knowledge about how to handle sensor-based real-time environmental data. The Deepwater Horizon blowout in 2010 is a notorious example showing that the availability of information does not directly imply its efficient interpretation by the different groups working on a platform. Initiatives to address this problem have already been taken elsewhere, e.g., the Alaska Ocean Observing System (http://www.aoos.org/) and the Monterey Bay Aquarium Research Institute (http://www.mbari.org).

A relevant project in the oil and gas domain was started in late 2011 by NorthOil[1], a multinational energy company. NorthOil awarded a consortium of international companies a three-year contract to design and develop a hardware and software solution to aid in the acquisition, elaboration, interpretation, modeling, and usage of sensor-based environmental data collected from the subsea fields. NorthOil's goal was to enable a cross-asset, standardized data representation and simultaneously to open the system to on-line environmental data. The added business value would allow NorthOil to more readily gain access from authorities to harsh Arctic areas where there are new discoveries of oil and natural gas. The project, EnviroTime, states that the process of real-time data handling from acquisition facilities to control centers should include *"the development of a semantic model (or ontology) to describe concepts, relations and properties within the EnviroTime domain."* Given the unexplored scenario, NorthOil purposefully left some uncertainty as to the end users. Members of the consortium are:

- *O&G Solutions*, a major supplier of IT solutions and sensor and communication technologies for the oil and gas industry, seeking a stronger business value in software and hardware integration;
- *ITCorp*, a world-wide provider of corporate technologies, with a long experience in realizing large systems for different business sectors, interested in broadening its role in semantic modeling by leveraging its own proprietary technology;
- *QualityCertificationBody* (*QCB*), a global service provider for certification and risk assessment, aiming at setting the standards for offshore environmental monitoring compliant with technological and modeling standards from international standardization bodies.

According to the shared documentation, the ad-hoc Design&Modeling group had the mandate to "*supervise the technical implementation during the project.*" For the purpose of our research, while keeping an eye on the overall situation, we focus primarily on what happens inside the Design&Modeling group to negotiate the realization of a semantic model.

The first author is a researcher from a Norwegian university who was granted full access to the offices of NorthOil beginning in March 2012, a few weeks after the official start-up of the EnviroTime project. Since then, she has been spending 2-3 full working days a week in the NorthOil offices. The second author has been an employee of NorthOil for 20 years as a senior researcher. This paper relies on the empirical data that the first author has been collecting over a period of one year as part of an ongoing longitudinal case-based study conducted in parallel with the design and development activities within the project. The study is ongoing as of March 2013. The findings are supported by the collaboration with the second author, thanks to his long experience in the oil and gas sector. Specifically, the activity took the form of ethnographic field work. Table 1 provides an overview of the main modalities of data gathering, the type of sources used, and the topics covered.

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[1] All proper names have been dubbed for the sake of anonymity

As a strategy to data processing and sense making, we adopted a temporal bracketing of the data collected during the ethnographic study into four phases to provide a unit of analysis and to identify the constraints of and reasons for the actors' actions (Langley, 1999). An interpretive approach has guided the process of data evaluation and interpretation (Walsham, 1995), informed by the seven principles presented by Klein and Myers (1999). The overarching principle of the hermeneutic circle, in particular, considers the interdependent meaning of the parts and the whole that they form. Given the number and the heterogeneity of the elements involved in the project we have analyzed, this principle guided our iterative data collection. For instance, since the beginning of the activity, the author has analyzed internal documents available on the NorthOil intranet, not only regarding the project itself but also with reference to the long-term strategies and views of the company. Having a broader knowledge about the actors helped the author to understand their choices. The entry point for the author's research activity was one NorthOil project manager. This may have affected the direct interactions with the other companies that subsequently occurred in semi-formal and formal settings. We acknowledge that this might be a limitation to the research, but having a key actor introducing us to the project was fundamental. In addition, we do not underestimate the value of allowing an outsider to be involved in the daily informal life and activities of an oil and gas company. This let us develop an understanding of the context that would most likely be impossible otherwise.

SOURCE	TOPIC/DESCRIPTION
Digital data sources	

- MS SharePoint team sites (Intranet):
  - Internal to NorthOil
  - Shared with partners
	- Long-term strategies and views of NorthOil
	- Private emails exchanged during the project (either internally or with partners)
	- Official reports and deliverables
	- Internal notes and presentations

Internet-based public information	- Official online information about NorthOil and its partners - Official guidelines and reports from the Norwegian Petroleum Directorate, the Norwegian Ministry of the Environment, standardization and certification bodies (e.g., W3C, ISO, etc.) - Reports on past environmental accidents
Semi–structured and unstructured interviews (transcripts)	
4 project managers from the GlobalMapping project	- Semantic technologies - Evaluation of GlobalMapping
9 participants in EnviroTime with different roles	- EnviroTime project, environmental monitoring in oil and gas - Relations between the EnviroTime project and past projects
Unobtrusive or participatory observations (field notes)	
- NorthOil internal briefing sessions - 9 teleconferences (1-6 h) with other NorthOil offices and with the partners - 3 workshops about EnviroTime	- Exchange of ideas - General issues in the EnviroTime project - Development of the semantic model
Other (field notes)	
- Informal chats - 3 conferences on science and practice in oil and gas - 4 full-day seminars at research centers	

Table 1. Overview of the empirical data sources.

4 Results

PHASE 0 – Background and context – In late 2011, NorthOil was executing a project in partnership with ITCorp to implement the GlobalMapping infrastructure to provide a global semantic model of production and asset data. The goal was to overcome the locality of data that is intrinsically due to the peculiar geological properties of the drilled terrain, the different structures of the wells and equipment, and the historically weakly coupled nature of the operations. In addition, different naming conventions have been established to refer to data stored on local information systems, causing a high level of fragmentation not only across fields but also across different disciplines. Standards are available for storage, but when a new or non-standard type of measurement is retrieved, it has to be handled manually by engineers to ensure quality and communication with other systems. The global model was intended to be based on a top-down ontology containing concepts from a number of well-recognized industrial standards. The need for a data integration solution was so great that many competitors showed a continual interest in the advancement of GlobalMapping. The project had been progressing for a few years, and, even though its start had been "fair enough", it was now struggling to move forward, mainly because of two factors. First, the technological choices did not allow scalability of the solution, thus constraining NorthOil developers to the proprietary pieces of code provided by ITCorp. Second, the lack of data standardization at the level of a single asset made the mapping of the data from local storage to the global model an obstacle. In addition, NorthOil management had difficulty mobilizing resources for the project, i.e., the local assets that were intended to finance the integrated solution did not recognize its utility. The NorthOil IT department took an active role in the development and testing activities performed by ITCorp and some misunderstandings arose between the developers at ITCorp and NorthOil. In spite of that, NorthOil hoped that the GlobalMapping solution would become a part of the installed base in a few months.

PHASE 1 – Lack of a common/shared terminology – In an interview conducted in October 2012, a NorthOil marine biologist tells about her experience with data management: "*I used for instance two months to get access to some videos. Depending on who did the service it was stored in different systems and to some extent the videos are not stored in any system at all because there is a link to find them on disks. So […] I see we definitely have no good system to get access to the existing data either. Of course those who use these data and collect these data on a daily basis then know where to find it. But for environmental-related issues there is already a large amount of information that is collected […], but for different purposes than environmental purposes then environmental people do not have access to it or it is very hard to get access to it because […] you need to know people to get access to hard disks or you need to know the system well to access these data. […] It is even worse to have data that are not accessible than to not have data at all.*" In 2011, NorthOil had performed preliminary tests in two fields at different geographical locations to remotely assess the impact of drilling activities on coral reefs on the sea bottom. The following practical issues emerged: How to make sense of mismatched readings from neighboring sensors? How to predict if the water current will take a discharge close to corals using a limited number of readings? To answer these questions, NorthOil initiated the EnviroTime project in early 2012. O&G Solutions was hired as the main partner and enrolled ITCorp and QCB. The contract the parties signed was composed of two sub-sections: a technical specification and a legal statement. According to a NorthOil project manager, the terminology used in the legal part to refer to the final product was left as open as possible because of NorthOil's intention to be the legal owner of the final product regardless of its format. The technical section of the contract required "*the development of a semantic model (or ontology)*" and made explicit reference to ITCorp's architecture currently under development for the GlobalMapping project. Additional shared documentation clarified the hierarchy of the project responsibilities. In the first version of the contract, ITCorp was intended to be the only partner in charge of implementing the semantic model. However, QCB demonstrated a strong interest in participating, and provided its own funding. A lack of a common definition of the concepts of "semantic" and "ontology" emerged early in the Design&Modeling group. It was not only a syntactic problem (using the word "ontology" as a synonym of "semantic model") but also a semantic problem in the meaning assigned by the actors to these labels. The following is an excerpt from the researcher's field notes taken during a chat with Rick from NorthOil: *"This done in a vacuum has allowed them to create a local terminology… QCB uses one, and ITCorp uses another […] We are at two completely different levels of communication."*

PHASE 2 – Negotiating the technology – A few weeks after the project's inception, NorthOil shared the descriptions of a few use cases that the EnviroTime solution should be able to handle. In particular, one case related to the long-term monitoring of a spectrum of ecological parameters in sensitive areas, and another to the detection of oil leakages in the production phase. The model had to be flexible enough to allow the end users to understand sensor data in specific situations, e.g., by integrating other vendors' systems, or despite missing information because of a lack of infrastructure (e.g., during the exploration phase). Rick issued a proposal to adopt a methodology based on Linked Open Data, which, in a nutshell, consisted of developing a "flat" graph of the data by describing common concepts by referring to other community-approved and publicly available graphs. He grounded his suggestions on the call for a use-case-based approach as defined in the technical part of the contract. As he stated during a meeting, *"We do not want to develop things that already exist but are slightly different*." On the other hand, Jim (ITCorp) and Martin (QCB) recommended that the development of an ontology represented in formal languages grounded on the aforementioned "oil and gas ontology" was the solution to obtain a standard-compliant model. They were making extensive reference to the legal part of the contract, liable to multiple interpretations. According to Jim: *"Maybe the use-case-based approach limits our view".* ITCorp's proposed design was based on the same software tools used previously in GlobalMapping, which would hinder NorthOil's aim to openly share data with research institutions to foster collaboration with other disciplines. Hans had a well-developed experience as a leading IT advisor in NorthOil. Doubtful about the approach to adopt, he expressed some practical concerns: *"With open source it is difficult to get dependable support when you need it. Many open source products are often very small… With a real support system you can call them always. (…) You get developers flown with helicopters to a platform (…) When you get [open source solutions]… they need to have the capability to fix any problem. You can run in emergency for no more than 10-12 hours. (…) When we buy things from ITCorp we know that we get this kind of support; but my concern is… where is the tradeoff with the issues of scalability, interoperability, etc.?"*

PHASE 3 – A need to focus on the data – After approximately half a year since the start of EnviroTime, the news was heard at the NorthOil research center; a decision had been made at the management level to stop the GlobalMapping project. This empirically confirmed how an excess of generification introduced too much disorder in the local assets. According to some NorthOil representatives, this new situation would leave the door open for new approaches to develop the semantic model for EnviroTime. However, on the other hand, this could suddenly halt the development process. Nonetheless, meetings and conference calls continued on a more or less regular basis. Based on the field notes, the researcher perceived quite clearly that ITCorp and QCB representatives continued to support their initial ideas. This is part of a conversation that occurred during a teleconference involving the members of the Design&Modeling group, specifically Hans and Rick from NorthOil and Martin from QCB:

Hans (NorthOil): *"We don't need an ontology; we need to be able to find out where to get the data. If it turns out that we need an ontology to do that then OK. But, I don't want an ontology until I know that I need one."*
Martin (QCB): *"Then you are not really interested in semantic web technologies."*

At the end of 2012, NorthOil settled for an approach inspired by Linked Open Data to foster a more efficient data combination in different contexts. For example, as the descriptions of the use cases proved, during the exploration phase preceding the drilling of a new well little or no infrastructure is in place, thus making metadata about the equipment less critical as they might be during the drilling phase. More focus was also set on the role of time in the use cases. The model should indeed support long-term tasks (e.g., monitoring the health of marine mammals) and shorter-term ones (e.g., the concentration of particles in water at a given time).

5 Discussion: mobilizing actors at a pragmatic level

When NorthOil first issued the invitation to tender a scope of work, its *problematization* (Callon, 1986), i.e., "how to achieve a semantic model of the environmental data?", placed the company as a passage point to solve the problem of developing integrated techniques to protect the environment during all oil and gas activities. NorthOil assumed that the development of a “semantic model” was the right solution and thus led the other organizations to find the answer in semantic technologies and to dynamically align around NorthOil’s target. Under the light of their business and historical background, their representatives have developed an experience and shaped their knowledge and understanding of concepts for which there remains a debate in literature and in the IT community. Participants faced a new and emerging type of knowledge, the management of real-time environmental data, and should adapt their background to it.

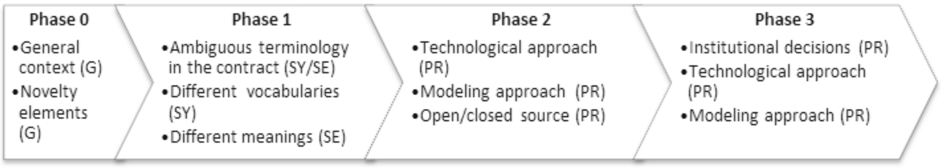

Figure 1 The boundaries at each phase and their nature (G=general; SY=syntactic; SE=semantic; PR=pragmatic)

Overcoming boundaries at a pragmatic level. The first step towards the successful management of knowledge is to overcome the syntactic barrier by transferring knowledge between communities (Carlile, 2004). In the analysis above (see Figure 1) a syntactic boundary emerges during phase 1, when different terms are used to refer to the same tools and no common vocabulary has been successfully shared at the start of the project. The second step would thus require translating knowledge to overcome semantic barriers. Our findings show no successful accomplishment of this process because the actors continue to assign different meanings to items that are labeled in the same way (phase 1). The words “ontology” and “semantic model” are used by each organization to imply different technological stacks and different modeling paradigms. The reach for shared terminology and sets of meaning is further disabled by the fact that the representatives of the organizations involved in EnviroTime seldom meet, and when they do, it generally occurs through situated arrangements (teleconferences or formal settings) where ambiguities can only be addressed temporarily, i.e., at an equifinal level. These first two obstacles mirror the present situation regarding semantic technologies reflected in the literature and in the IT community. The consequence is a lack of capability of the shared artifacts to foster a discussion of the impact of technological choices on the final outcome in situations where the future remains unclear. A successful design phase entails predicting the role of given artifacts as boundary objects. However, they often emerge in use (Levina and Vaast, 2005) and can only be observed after a pragmatic test. The semantic model thus acts as a boundary object to catch the tensions emerging in the EnviroTime project; it is the battlefield where collaboration plays out, the reason for further negotiations, and the trigger for an improved understanding of key environmental aspects. Interestingly, semantics themselves also constitute a semantic limitation to collaboration. The lack of a syntactic and semantic capability within the negotiation process could thus be seized at a pragmatic level. This step requires the transformation of knowledge so that political barriers (interests) are set (at least temporarily) aside (Carlile, 2004). In phase 2, actors’ different explicit and implicit agendas are revealed from the historical background and the business sectors of each company. If and when they meet, the organizations’ representatives must act at a pragmatic level. During an informal chat, Rick (NorthOil) argues: “*I suppose the big picture is that the partners are misaligned. That the understandings and approaches diverge greatly, and that there is no way to mediate between them because NorthOil views this as a research project and O&G Solutions view it as an engineering project. This is evidenced at the small scale by various things. But oddly not semantics, where everything is reversed. NorthOil is "this isn't the research part, it is engineering" and ITCorp + QCB want to create new knowledge.*” Innovation can happen through collaboration by the inscription of the actors’ interests on the final outcome; however, such capability was not enough in the analyzed case until Hans clearly reminded the partners of the final outcome, i.e., the possibility of representing real-time environmental data in different contexts and time windows. Figure 1 shows how syntactic and semantic misalignments trigger pragmatic obstacles, which are, in turn, to be motivated on a more abstract level by accounting for the institutional and historical backgrounds both of the actors involved and of the technology adopted. No first-level obstacle (like a lack of a common terminology) can be understood without digging beneath the surface for pragmatic and institutional discrepancies with deeper roots.

The information infrastructure rationale of environmental monitoring. Semantically enabled solutions (and ontologies in particular) are, after all, technological artifacts. They are a technology in use (Orlikowski, 2000) that should represent information in a manner both recognizable by and enabling of the knowledge of the specific social context they attempt to target. Indeed, evolving forms of collaboration continue to exist in each of the communities of users of an information infrastructure. Communities tend to maintain their own tasks, practices, and pre-existing information systems, thereby often refusing a standardized model or not recognizing their own knowledge in it (Hepsø et al., 2009). As Hepp (2008) noted, “ontologies are not just formal representations of a domain, but much more *community contracts* about such formal representations” (p.6, emphasis in original); they are supposed to be the result of a negotiation process, a temporary state of shared knowledge that reveals meaningful insight in a given context. The technological element has therefore to be considered as a primary actor and analyzed by the way the users and the broader IT community use and understand it. In line with ANT, the view of technology in use as a socio-technical network allows us to conceptualize semantic technologies as more than just part of an information infrastructure. They can be considered information infrastructures themselves. Their development follows a process of translation comprising not only developers and users but also the overall background in which the technology was born, and the domain whose knowledge it represents. Semantics are an especially interesting case because of their troublesome story and their explicit attempt towards the representation and management of the knowledge of a domain. At a higher level of abstraction, our case represents a shift for the entire oil and gas business domain. Well-established practices and standards co-exist in the tasks related to operation and management (Hepsø et al., 2009, Monteiro et al., 2012, Rosendahl and Hepsø, 2013) and a degree of irreversibility (Monteiro and Hanseth, 1995) in the traditional approach has already been reached. The addition of novelty elements lets new invisible actors emerge in the socio-technical network hidden under a technological artifact. In our story, underneath the semantic model lies what Law and Singleton (2005) call an *absent presence*, the environment. Within the EnviroTime project, the marine environment is made physically present thanks to the deployment of heterogeneous sensors on the sea bottom to capture the behavior of the marine ecosystem. Its progressive incorporation in the traditional oil and gas ecosystem is the rationale for adopting a perspective based on information infrastructure. The semantic model was motivated from the beginning as the key instrument to give a real-time voice to the environment, even if corals and fish are never physically present in the Design&Modeling group meetings. It is one of the socio-technical (or, more broadly, sociomaterial) artifacts (Orlikowski and Scott, 2008) that should enhance the process of mediation through which environmental knowledge is made part of the oil and gas culture (Latour, 2004). The ability of the semantic model and of other actors’ agendas to speak on behalf of the environment could represent the very outcome of the innovation project described in our story; hence, a pragmatic achievement of knowledge transformation (Carlile, 2004). There lies what Carlile and Lakhani (2011) call the “sweet spot” of innovation. This can be described as a problem of mobilizing actors by pushing disagreements back far enough, or *equifinally*, by giving a voice to those elements that should be the main motivation for innovation, but are often forgotten.

6 Conclusions and implications

In this article, we described the innovative attempt of an international oil and gas company (NorthOil) to enhance its real-time environmental monitoring capabilities as a consequence of the latest technological advances. This scenario represents a unique opportunity for the domain to abandon the local, fragmented practices in information management and head towards more integrated, cross-organizational networked solutions for more efficient decision making. We depicted the trajectory of a collaborative project to reach an *equifinal* level of understanding in spite of the unresolved ambiguities that arose. The following question now remains: What are the implications for the sociomaterial practices through which environmental information is daily handled by oil and gas operators? The project we studied spans across three years and is therefore ongoing; nevertheless, we are able to draw some conclusions. Each of the approaches proposed by the participants to the design process has consequences on the capabilities of the final result. On the one hand, the path towards a top-down, standard-based semantic model could lead to the re-establishment of a degree of irreversibility because of the inability to conceal heterogeneous distributed information sources. We illustrated how a previous project demonstrated the practical and technological complications of this approach. On the other hand, a solution based on the Linked Open Data set of practices was proposed as the right tradeoff between a top-down modeling methodology and a bottom-up categorization based on the data managed locally by users. The test field for this latter approach is even more interesting because environmental monitoring has historically remained almost virgin to oil and gas traditions. Even so, this path could be practically, or pragmatically, unfeasible. It could either be misunderstood in the domain where it has to be used, or it could be viewed as immature because, after all, the oil and gas sector is an intrinsically closed domain. As we illustrated, the attempt by NorthOil to cover every possible final product of the project in the bureaucratic sections of the contract attracted the attention of the partners and opened the box of ambiguities about the nature of the final product. To conclude, a pragmatic (or, again, equifinal) conceptualization of the role of semantic technologies as information infrastructures is relevant at three levels. For the oil and gas sector (i), to understand *how* a given modeling methodology can enable the effort of extrapolating a timely meaning from the punctuated sensor network through which the environment is made present. Symmetrically, it is fundamental for IT developers within oil and gas (ii) to clearly realize how a given technology could enable or disable future improvements, e.g., by taking into account newer combinations of data to make sense of natural phenomena. Finally (iii), our analysis is an indication to the information systems research community to focus more on the implications of specific technological elements inside information infrastructures.

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Paper II

Paper 2

The Facets of Sociomateriality: A Systematic Mapping of Emerging Concepts and Definitions

Parmiggiani, Elena and Mikalsen, Marius

In Nordic Contributions in IS Research Lecture Notes in Business Information Processing
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Paper III

Paper 3

Sociomaterial Capabilities in Integrated Oil and Gas Operations - Implications for Design

Parmiggiani, Elena; Mikalsen, Marius; and Hepsø, Vidar

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SOCIOMATERIAL CAPABILITIES IN INTEGRATED OIL AND GAS OPERATIONS - IMPLICATIONS FOR DESIGN

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SOCIOMATERIAL CAPABILITIES IN INTEGRATED OIL AND GAS OPERATIONS – IMPLICATIONS FOR DESIGN

Complete Research

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Abstract

Organisations must design and innovate capabilities in a symbiotic evolution between social and technical elements. Information Systems (IS) literature has successfully demonstrated the relationship between the material technology and the social organization, and how both influence each other. However, research has tilted in terms of favouring the explanatory power of either social or material agencies. To address this we suggest viewing the relationship as a sociomaterial capability addressing key organisational objectives. To understand the role of IS in such a capability, an approach addressing the bi-directional and flexible relationship is needed. We explore sociomateriality and draw empirically on a holistic case study in an international oil and gas company. The result shows how two sociomaterial capabilities, convergence and maintenance, are performed to contain tensions between global requirements and local contexts and between rigidity and flexibility. Second, bridging capability with the information infrastructure design theory, we derive seven principles for information system design to support organisations.

Keywords: Sociomateriality, socio-technical, capability, flexibility, convergence, maintenance, case study, design and innovation, information infrastructure.

1 Introduction

Modern subsea oil and gas exploration and production are characterized by particularly expensive and risky operations across complex information infrastructures, including exploring potential underground and/or subsea oil and gas fields, drilling exploratory wells, and subsequently drilling and operating production wells. To operate safe and cost effective, the oil and gas industry has turned its attention to the notion of *Integrated Operations*, as a strategy towards the integration of people, work processes, governance, and technology with the goal of improved decision-making and better execution. To achieve these goals, ubiquitous real-time data, collaborative techniques, and multiple expertise across disciplines, organizations, and geographical locations are sought utilised (Rosendahl and Hepsø 2013). In operations that "integrate" the social (people) and the material (technology), the Information Systems (IS) literature has demonstrated the mutual influence between the social and the material. Technologies alter the "*social dynamics*" of organizations; be that change in organizational structures, decision-making and power relationships in formal organizations (Barley 1990), or change in informal communication networks (DiMaggio et al. 2001). Reversed, research also documents the malleability of technology, explaining how technologies emerge as products of a social process; negotiations, human agency and personal interest (Leonardi and Barley 2008). It is well established in practice-based perspectives that the use of information systems is subject to local tinkering and adaptations (Suchman 2006; Monteiro et al. 2012b).

While these unidirectional influences are well rehearsed, it has proven more of a balancing act to account for how the social and the material, through a bi-directional network, dynamically perform together. Instead, tilting has occurred, giving more explanatory power to either social or material agency, resulting in "*theoretical accounts that are epistemologically and ontologically unable to handle the entwining of the material and the social and that cannot speak with precision about degrees of agency and constraint*" (Leonardi and Barley 2008, p.161). Since Orlikowski started questioning the separation between the social and material (Orlikowski 2007), a wave of contributions on sociomateriality has come (Constantinides and Barrett 2012). It is now suggested to consider contributions on sociomateriality along a continuum ranging from "hard" sociomateriality to "soft" sociomateriality according to how they conceptualise the relationship between the social and the material (Mikalsen 2014). On the hard end of the scale we find Orlikowski type contributions, building on Barad´s agential realism (Barad 2007), asserting that the social and the material are "*inextricably related – there is no social that is not also material, and no material that is not also social*" (Orlikowski 2007, p. 1437). Toward the softer end of the continuum we find studies that conceptualise sociomateriality as a coupled or linked relationship between two separate entities. Kautz and Jensen (2013) see Leonardi as being one of the main proponents of this end of the continuum, using the concept of imbrication "*to capture the simultaneous interdependence and specificity of each the digital and the non-digital. They work on each other but they do not produce hybridicity. Each maintains its distinct irreducible character…*" (Leonardi 2011, p. 151). Both the hard and the soft versions of sociomateriality is at the centre of current IS debate (Mikalsen 2014). Mutch (2013), has argued from a critical realism stance that Orlikowski-type studies where the material and the social is not seen as separate entities (hard sociomateriality) lead to "*confusing levels of analysis*". Leonardi-type studies, perhaps closer to the actor-network theory (ANT) roots (soft sociomateriality) (see (Latour 2005) for a recent summary of ANT), is also critiqued, albeit on contrasting grounds. Pollock and Williams for example argue that such ANT based contributions with their focus on following local actors fail to explain how sociomaterial imbrications are shaped across space and time, and that we need a more "*contexted view*" (Pollock and Williams 2011).

The concept of sociomaterial capabilities that we explore here reverberates with the softer and perhaps performative stream of this sociomaterial research that acknowledges that both social and material agencies have the capacity to exercise a great deal of flexibility (Leonardi 2012; Parmiggiani and Mikalsen 2013) in the way the imbrications play out and are performed in practice. In fact, it is only through flexible imbrications they can be considered *capabilities*. This becomes evident as we view capabilities, as Henderson et al. (2013) do, explain capabilities as an extension of process thinking in organisations that has been limiting in terms of trying to define "*perfect*", "*to be*" processes that in effect fail to reflect a complex organisational and technical reality. In order to prevail, process thinking needs to account for sociomaterial imbrications as *"…alignment of process, people, technology and governance. […] The notion of a capability emerged as an explicit attempt to cope with this complexity.*" (ibid, p. 5) Capabilities are configured to reach a defined business objective, e.g. to find oil and/or natural gas. Key to capability thinking is that value comes from the combination of factors, not the individual factors alone. People, processes, technology, and governance (strategies) are configured to create an organisational capability and business value. As a consequence, designing information systems to be a part of a capability, and consequently business value requires an understanding of the capability context – the way those four elements are combined in existing and new configurations. In this view, technology is not dismissed as static and fixed representations, but rather something performed. The meaning and use of technology is not something given, but rather emerges in practice. Human and material agencies interact directly, but they still are distinct phenomena, that, at certain points in time, for a given purpose, become imbricated. Sociomaterial capabilities are people and technology "*interlocked in particular sequences*" that can "*produce, sustain, or change*" routines and technology (Leonardi 2011). We will show how the imbricative formation of a capability does not happen in a vacuum, but is rather the result of balancing conflicting goals and containing dynamic tensions (Smith and Lewis 2011). This becomes particularly clear in Integrated Operations as the capability reaches out of the local and situated (Suchman 2006), integrating social and material actors across dimensions of space and time, extending our notion and understanding of "situated" knowledge (Pollock et al. 2009). Succeeding in innovating and designing capabilities consequently require insight in the tensions faced, and practical strategies applied in capabilities to deal with these tensions.

The two research questions addressed in this article is therefore; *i*) how is flexibility performed in sociomaterial imbrications (forming capabilities)? And, following from the first, *ii)* what are the implications for designing the information system part of such a capability?

To answer these research questions a holistic case study of two capabilities from the upstream oil and gas industry is reported. These cases' critical characteristics make it particularly attractive to study the performativity of sociomaterial capabilities. The only way that people can know anything about what happens deep down subsea and subsurface – without actually performing an expensive and potentially hazardous drilling – is *indirectly*, through sensor data brought to them through information systems. Based on these data, professionals need to make their decisions. Is it oil down there? Can we drill safely? The empirical setting is NorthOil (an acronym), a large international oil and gas company that perfectly illustrates the tensions facing this kind of operations, and, equally important, how the tensions are contained.

The first case presents tensions between the local sites and the global infrastructure in an initiative for environmental monitoring that NorthOil is running due to the necessity of drilling in an environmentally sustainable manner, particularly when moving into diverse and fragile biological habitats. We conceive of the capability to keep this balance between local and global as *convergence*, a notion openly defined by Bowker and Star (1999) as the process by which infrastructures and the social world come to fit to each other. It hermeneutically stresses the fundamental role of the imbrication between humans, technology and nature at the local site to generate a global result.

The second case presents tensions between the need for formal procedures to assure the quality of work and the flexibility needed in order to keep up or improve performance. These tensions result in containment strategies in NorthOil´s exploration department. We conceptualise this containment as the capability *maintenance* (Graham and Thrift 2007). Maintenance in this regard is the invisible (until breakdown) processes and tools that are perhaps seemingly mundane but indeed necessary components in discovering oil and gas.

The article is structured as follows. Next, in section 2, we introduce the case studies at NorthOil and explain how we study the sociomaterial capabilities. In section 3 our main findings are spelled out in terms of two central tensions observed in the empirical cases; the tension between the local and the global, and the rigid and the flexible. We show how the containment of these tensions forms two sociomaterial capabilities, *convergence* and *maintenance*. In the discussion section we explain six IS design implications that the designers for sociomaterial capabilities in organizations should adhere to; *i*) opting for value-driven design, *ii*) utilizing the information legacy, *iii*) accounting for multiple materiality, *iv*) KIS (keep it simple), *v*) ensuring sociomaterial modularity and frictionless data and finally, *vi*) including the maintainer in the design process. We conclude by drawing some implications for practice and further research.

2 Method and study context

2.1 Empirical setting

NorthOil is an international oil and gas company established in the 1970s and headquartered in Northern Europe, currently employing over 20000 people with activities in 35 countries, with a focus on the Norwegian continental shelf. NorthOil's primary activities are the exploration of new oil and gas fields and the operation and maintenance of a number of offshore production installations. We theoretically sampled two case sites in NorthOil, also guided by pragmatic concerns of access. Our study is therefore a multiple-case holistic study, in that we studied one phenomenon in each of the two cases (Yin 2009). The two cases can be defined as critical cases, as they have strategic importance in relation to the general problem (Flyvbjerg 2006). They illustrate how capabilities meet tensions in practice in a domain like that of offshore oil and gas where the objects of interest – the subsurface reservoir and the subsea operational area – are only accessed through sensors and information systems.

In the first case, we look at NorthOil's effort to develop an infrastructure for real-time subsea environmental monitoring. Over 60% of the oil production on the Norwegian continental shelf comes from facilities installed on the sea floor. As the company´s activity moves towards environmentally fragile areas (e.g. the Barents Sea), authorities require the prevention of environmental damage caused for example by the possible discharge of drill cuttings during drilling, or by the deployment of rigs and pipelines. That implies that the traditional preventive approaches involving bi- or triennial campaigns where ships go out and collect data are no longer sufficient. With the traditional procedure, data are usually collected offshore and later analysed onshore, with temporal gaps of 9-12 months. The process of monitoring the marine environment is today undergoing a development process, boosted by new technologies and integrated collaborative tools. Sensor networks to measure several operational and environmental parameters are deployed and data can be accessed in real-time thanks to fibre-optic cables, radio and satellite communication. To enable a more proactive assessment of environmental risk, in late 2011 one department at NorthOil's research centre initiated the EnviroTime (an acronym) project to leverage the recent technological improvements and integrate subsea equipment with environmental observatories for the real-time surveillance of the marine ecosystem.

In the second case, we look at the process of maintaining the infrastructure for supporting data interpretation in NorthOil's exploration department, where geologists and geophysicists ("G&G personnel" or simply "G&G") are essential to interpret the company's vast amount of subsurface data. Geologists know rocks and the formations they make in the earth crust. Geophysicists focus on physical characteristics, such as magnetics and gravitation to analyse subsurface rocks and formations. To do this, all available data from previous and on-going exploration projects are sought used in order to extrapolate a model of the area of investigation, and try to find the presence of hydrocarbons. Drilling is the only sure way to find out if oil and gas exist somewhere down in the earth crust. However, since drilling is highly expensive and potentially hazardous, they try to keep drilling to an absolute minimum. Instead, they apply information systems combined with human expertise to make interpretations of the subsurface, thereby attempting to predict, to the best of their ability, the presence of hydrocarbons.

2.2 Data collection and analysis

This article draws on the empirical data that the first two authors have been collecting as part of two ethnographically inspired longitudinal case studies. We were granted access to NorthOil research centre in April 2012, and the second author has been spending there an average 2-3 working days a week since then doing participatory observations, interviews, and studying internal documentation. In March 2013 we were granted access to the NorthOil exploration case, and the first author has been present there in five periods for 14 days total, combining participatory observation and interviews. Both cases are still ongoing. Table 1 below provides an overview of the modes of data collection. In particular, the observations include participating in meetings, conferences, being co-located at the workplace, and talking informally over lunch and coffee. We have hundreds of pages of field notes. The interviews are all semi-structured (Myers and Newman 2007) and have been generally conducted by asking few initial questions about the interviewee's experience in NorthOil or in the domain considered (environmental monitoring; oil and gas exploration). Thus, the script was intentionally left flexible to allow the researchers span across different topics following the interviewee's answers and reactions, but making sure that the planned points were covered during the available time (1 to 1.5 hours on average). Interviews have been audio recorded and selected parts were transcribed.

SOURCE	TOPIC/DESCRIPTION
Digital data sources (documents)	
MS SharePoint team sites (Intranet)	Long-term strategies and views of NorthOil Private emails exchanged either internally or with vendors Official reports and deliverables Internal notes and presentations
Internet-based public information	Official online information about NorthOil and its vendors Official guidelines and reports from Norwegian and international authorities
Semi–structured and unstructured interviews (transcripts)	
5 data managers in the exploration	Data and data management
18 participants in EnviroTime with different roles (project managers; environmental advisors; IT advisors) 3 participants to EnviroTime from partner companies (1 project manager; 2 environmental advisors)	EnviroTime project, environmental monitoring in oil and gas Relations between the EnviroTime project and past projects State of the art in environmental monitoring Data modelling solutions
Participatory observations (field notes)	
14 full days with NorthOil data managers	Sharing key documents, presentations showing systems and

	processes
2-3 full days a week (April 2012 – December 2013) with EnviroTime participants EnviroTime weekly briefing sessions (variable length) 13 teleconferences (1-6 h) with other NorthOil offices and/or vendors 4 workshops about EnviroTime	Exchange of ideas General issues in the EnviroTime project Application of data modelling techniques Usage of environmental data together with operational data
Other (field notes)	
Informal chats over lunch and coffee 3 conferences on science and practice in oil and gas 4 full-day seminars at the research centre	

Table 1. Overview of the four modes of data collection: document study, semi-structured interviews, participatory observations, and informal chats.

An interpretive approach has guided the data analysis process (Walsham 1995). In practice, we subscribed to the principles proposed by Klein and Myers (1999). The first principle is that of the hermeneutic circle. It helps to account for the interdependent meaning of the parts (e.g. the participants' understandings) and the whole that they form (e.g. the meanings emerging from the interactions between the parts). We followed this principle in our strategy to data analysis and sense making by iteratively adopting an inductive-deductive approach. As mentioned, the initial choice of the case material was based on theory, in particular on sociomateriality as a theoretical lens. According to Walsham (1995): "*The motivation for the use of theory in the earlier stages of interpretive cases studies is to create an initial theoretical framework which takes account of previous knowledge, and which creates a sensible theoretical basis to inform the topics and approach of the early empirical work.*" (p. 76). Walsham later invites interpretive researchers to remain open to new ideas from the field data. An inductive approach was thus followed as we open coded the material to identify the emerging themes inside the material and to progressively refine them through the discussions between the authors. Subsequently, the sociomaterial capabilities have been identified out of the data. This process has been complemented by deductively drawing on theoretical concepts that inspired the labelling of the two capabilities.

The second principle is that of contextualization. It underlines the importance of understanding the subjects of a study as a part of broader social and political contexts. The study of the design and implementation of information systems and infrastructures cannot be decoupled from the bureaucratic, business, and technological context where it is happening. We operationalized this principle thanks to a constant collection of official and informal documentation both from NorthOil and the competent authorities, to gain an historical overview of the policy regime under which NorthOil operates and the management's past and future strategies. The documents include access to NorthOil team sites (intranet), selected documents sent to us, and public information. The third author, thanks to his 20 years of experience as a senior researcher in NorthOil, gave an important contribution by facilitating the access to relevant documentation and to get a more thorough overview of the company's background and context.

The third principle deals with the interaction between the researchers and the subjects in a study. It acknowledges how data are produced by the social interaction between the researcher and the participants, in that the participants have a role in interpreting and analysing information. We put this principle in practice by making extensive use of participatory observations. As our access to the empirical settings improved, we have been increasingly accepted by NorthOil's employees and have been asked for feedback or to take part in small tasks (e.g. commenting on the draft of a document; helping in formatting a report).

The fourth principle guides the drawing of abstractions from the particulars. Abstraction can take several forms (Walsham 1995). We chose to draw specific design implications (see section 5).

The fifth principle requires openness to the prejudices that guided the original research design. We applied it by iteratively discussing our findings with the research group we belong to and by constantly interacting with the participants in our case studies (see principle three above). In addition, this principle accounts for our adoption of narratives to focus on interesting aspects of the relationship between the emerging tensions and the sociomaterial capabilities required to address them (see next section). Narratives help to reproduce observed situations characterized by variable temporal embeddedness, eclectic data, and no clear boundaries (Langley 1999).

Principle six warns against ignoring the broader social context conditioning the observed human actions. Accordingly, we chose to let different types of informants speak. This strategy is apparent in our choice of interviewing participants with different roles in the case studies. In the EnviroTime project, we could for instance interview also one project manager and two environmental advisors from two vendor companies.

3 Tensions require Convergence and Maintenance

3.1 Tensions between the local and the global require convergence

Several wells can be drilled in an oil or gas field. As of 2012, NorthOil was operating hundreds of productive wells in the world. The geographical distribution of wells entails a stark heterogeneity in the geological characteristics of each site. As stated by the commission in charge of investigating the Macondo blowout in the Gulf of Mexico, each well has its “own personality”: knowledge about local conditions of the rocks to be drilled, the particular installation, and the surrounding marine environment have to be developed and tailored to the local setting (OSC 2011). Different technological configurations must also be adapted to local environmental constraints. Expensive solutions for harsh weather in the Arctic North might not be suitable for the sea floor off Brazil. In addition, technological innovation is an important factor. Operations are becoming increasingly dependent on lightweight subsea installations completed on the sea floor and remotely operated and monitored from a control room via e.g. fibre-optic cables (Hepsø 2008). NorthOil has been in business for over 40 years. In spite of the recent call for Integrated Operations, four decades of divergent activities have resulted in the accumulation of a wide spectrum of heterogeneous information over several diverse and often overlapping information systems and operators have created local strategies and workarounds to carry out their tasks (Østerlie et al. 2012).

National governments and international organizations issued guidelines and regulations to monitor and assess subsea risk (NME 2008; OSPAR 2009). Oil and gas companies must develop devices and methodologies to predict possible effects on the biological resources to be granted a “permission to drill” in environmental sensitive areas. However, no comprehensive regulatory framework is today available. Environmental monitoring is therefore a task characterized by uncertainty and complexity. First of all, uncertainties remain with regard to the technology and the monitoring practices to use in the local biological ecosystems. For example, the Norwegian continental shelf is home to the world’s largest population of cold-water corals. In 2011, NorthOil performed some preliminary tests to simulate the environmental impact of a new well onto a protected coral reef in the vicinity and to assess the viability of the EnviroTime project. Oceanographic parameters (e.g. water currents, pressure, particle sedimentation rate) had to be monitored in order to predict whether discharges of particles would be taken close to the corals by the current. As no data-transfer cables were available in the chosen point, a surface buoy had been connected to the sensors on the seabed to send real-time data onshore through to a satellite link. The real-time data transfer was initially successful, but the buoy went suddenly lost after a few days. NorthOil had to plug in third-party software to model oceanic currents and infer the missing data to provide the authorities with a sufficient report:

> “So in that way we were able to fulfil the real-time environmental modelling during this whole drilling period. So this modelling was updated every hour so we could have a new picture of the current situation at the location, the concentration of particles in the water column at different coral structures and also sedimentation of particles on the seabed at different locations. At least we have that overview. This worked very well with this backup solution but in the future of course we should have it as current data that have to be in place. (…) But this is the typical problem we do have, it is not the first time, I think it has happened 3 or 4 times before, this happens because we are still working on having equipment on the sea that are robust enough.”
>
> (Environmental advisor, Interview, December 2012)

This empirical snippet is a good example of the difficulty to control infrastructures as pointed out by Ciborra (2000). They are made to standardize natural or social phenomena that are themselves uncontrollable. A daily bricolage work is required to cope with situated constraints and to fulfil top-down standardization requirements by integrating the new systems (e.g. real-time data collection, wireless communications) with the old infrastructure (real-time calculation of risk with well-known modelling systems). Subsea environmental monitoring has a performative nature. It is the result of an emerging interlocked sequence of material elements (the sensors; the modelling systems; the corals and the water currents; the particles discharged while drilling); human knowledge required to interpret the sensor-filtered data; national or regional norms to be fulfilled; and the establishment or adaptation of standardized work processes. All these elements get imbricated to make a decision regarding a possible state of risk of a specific submarine area. In particular, nature plays a key role in this imbrication for at least two reasons. First, the technical equipment must be “robust enough” against the local weather conditions. In the excerpt above, a company internal assessment concluded that the buoy had most likely been cut away by vessels passing the area during bad weather. Second, the types of data to be collected and managed depended on the presence of given species of protected fauna in that specific area where NorthOil wanted to drill new wells, making the monitoring activities also a complex work. Corals are a static resource and can be inspected through sensor racks and cameras from a fixed position. Fish is instead more unpredictable, as its movements have to be tracked not simply along three axes. As indicated by a leading advisor in the EnviroTime project:

> “So in order to build the complexity of the EnviroTime solution I think it is important that you select a different type of resource [in addition to] corals, I think it is important a pelagic resource like fish, plankton, that lives in the water masses, and it has a 5 dimensionality, not only 3. Because they have a position, and they are at a certain depth, they have also a concentration, and at a certain time. (…) What parameters do you need to collect, what should be the resolution of the parameters you collect, how many [subsea sensor networks] will you need to get sufficient amount of data to plan your operation? Will you need one lander location? Will you need 4? 10? To say something about the resources in these 5 dimensions. And of course that would give some challenge to the data management because it’s a lot of data, complex data, and how should it be visualized”
>
> (Leading Advisor, Interview, 2013)

It is difficult to predict the behaviour of moving marine biomass or their reaction to the devices used for inspection. In November 2013 we were interviewing an IT advisor involved in the development of a web portal to display real-time data retrieved by a test sensor installed off the Norwegian coasts next to a coral reef. On his computer screen was the browser, open on the web interface displaying the incoming real-time data. At one point the interviewee was distracted by a fish coming out of the reef and stopping in front of a live camera images. The fish stopped for a short time, and then disappeared again. The IT advisor told us that it was not the first time that fish did so, and the analysis of the acoustic data indicated that it also used to “say” something:

> “And that’s what happens, he gets really angry so he says “Shshshshsh! (…) Or maybe he gets annoyed. Maybe he gets used to it. And that’s also one of the things. Will we influence, will the local fauna get used to the sounds when we do the stuff?”
>
> (IT advisor, interview, November 2013)

3.2 Tensions between the rigid and the flexible require maintenance

The geologist and geophysicist (G&G) personnel in the exploration department must cope with enormous amounts of subsurface data. The three main types of data used by G&G are seismic data, well data, and production data from existing wells. Seismic data are gathered using ships equipped with air guns firing acoustic pulses down through the ground. The echoes that come back show different rock layers and depths. Well data are logs gathered while drilling a well, showing the well characteristics. Production data are data from wells that already are in production. Taken together these data sources form a base of data upon which the G&G personnel can create interpretations.

The amount of data is huge. Data are primarily gathered from two main sources, the corporate raw data store and a national database where all oil and gas companies operating on the Norwegian Continental Shelf are required by the law to store all of their seismic, well, and production data. The database has thousands of tables and thousands of attributes. Central data managers (CDMs) administer the corporate data store. G&G (and other interpreters) need to extract data through queries that involve joining 20 to 30 tables that are run overnight. In-house IT specialists (such as e.g. "GIS experts" and project data managers or PDMs) are called for in order to formulate and execute these queries. These experts are co-located in the same physical office space as the G&G personnel to be close to the exploration operations. The goal is to facilitate cooperation and to build knowledge of the work that the G&G do, in order to better understand what the G&G actually need. Another issue is the number of systems involved. There are 35 different systems, ranging from petrophysical evaluation to corporate data stores and data integration tools. IT experts (in house and external) are needed in order to enable the data to flow to and from this ecosystem of tools.

Overall, and simplified for descriptive purposes, the process of exploring a certain geographic area consists of three main steps. First, a new exploration project is created and is populated of existing data from the national database and the corporate data store. PDMs and IT specialists assist the G&G in this process. Second, G&G start working on the data, doing their interpretations. More data can be called for, e.g. more or new seismic surveys, and data can flow into the system in real time, e.g. from exploration wells that are drilled. These data are taken care of by PDMs and consultants. Finally, when the project is finished (found oil or not), data are tied up, quality assured, and entered into the corporate data store for future use. This is a complex process involving a lot of different people, roles, processes, and technology. There is a tension between the obvious need for NorthOil to define proper processes for this, and the actual dynamics of the operation.

The rationale for having well-defined processes is clear and sensible. A NorthOil process owner explains why the need is there:

> "If not it would be chaos. Too many applications and solutions, it would be very hard to support all of them. Also, it is about standardization. A person should be able to leave one business area and go to another one, and then start working immediately, with the same machinery and tools he is used to″
>
> (Process owner, from field notes)

Immediately that makes sense, and at critical parts of the exploration process definitions are indeed followed. One reaches for example certain decision gates (e.g. to do drill an exploration well), where one makes a decision, documents the rationale for that decision, and stores it into the data stores. But, in order to make it work, there is a need for a dynamic (that is; not predefined and rigid) activity of people and technology. A PDM explains the relation to the process definitions:

> "We lack a good enough process for data management. There is no standardised way of entering data into the system, for instance well data from an exploration well. The real data flow is known to a PDM after two to three years of practice. You start to know what is happening, but then things change, and you do not necessarily get notified. We have a community portal, but it does not suffice, particularly not for inexperienced people"
>
> (Project data manager, from field notes)

The formal process description defines how at the beginning of the exploration of an area, a new project should be started in the project data store, where new data should be propagated. However, rather than following this protocol, the G&G extend existing ones in geographical proximity to the area of interest. This has a very practical reason. The G&G know that they have a lot of relevant information in the existing projects and want to make sure to bring all of that with them into the new project as well, to make sure nothing is lost.

To be able to deal with this rather "messy" reality and lack of well-defined processes and tools, flexibility is observed in both people and information systems. There are many roles in NorthOil exploration solely working on providing the G&G personnel with the data they need. The PDMs for example are co-located in the same physical department as G&G personnel. Until recently they were even co-located in the same offices. The reason for this is to have a proper understanding of what the G&G personnel need and to understand "*what they really are asking for*" (from field notes). The PDMs attend meetings; receive e-mails, phone calls, and in-office requests from the G&G data access and maintenance. The PDMs exercise flexibility in terms of answering to requests from the G&G. Below is an example where the ideal process is not followed, but flexibility is exercised to overcome the contingencies in the situation:

> "A PDM has earlier that day received an email about preparing some well paths in the project data store, so that it is ready to receive real time data from the drilling. The PDM calls me over and says that he shall be very open. It is something about communication. He tells me that during a [coffee] break outside, he has met with a G&G person that told him that it is one week until SPUD (drilling shall start) and that the names of the wells are set. Four well paths must be prepared in the project data store and the PDM is somewhat frustrated that he has to learn this accidentally in a break, and he feels that the original email sender should have informed him about the fact that SPUD is in one week, and that a name etc. has been set. He says, it will work out anyway, I would have gotten notice maybe a day or two before SPUD, but then it would get very hectic. I ask him why he did not get the message that SPUD was in one week, and he says it is '*a new guy*'"
>
> (Project data manager, from field notes exploration, 2013).

The ICT tools must exercise flexibility too. In the absence of inter-tool application interfaces, IT specialists, such as GIS experts, are co-located with the G&G personnel to ensure data flow into GIS tools such as ArcGIS. They write SQL queries to interface the corporate database and Python scripts to extract the data. The data they extract are tailored for presentation in the GIS tools in a way feasible to the G&G personnel. Since the G&G cannot do this directly, and in order for the IT specialists and PDMs to be able to do this, the tools have at least a minimum kind of flexibility that enables them to take data out of one system, work with it (format and quality assure), move it to another system, and present it in a certain tailored way in another tool.

4 Implications for Design

4.1 Designing sociomaterial capabilities

Investigating the bi-directional relationship between the social and the material is key to IS knowledge, but it has proven challenging as researchers have treated "*human and material agencies as having a unidirectional relationship*" (Leonardi 2011, p. 148). Now, more technology is designed with flexibility (customisability and adaptability) in mind, either by the users themselves or by IT savvy personnel (developers and/or IT support) in the organisation (ibid.). Instead of addressing the social and material as separate entities, many scholars now view and try to explain them in the form of "*constitutive entanglement*" of the social and the material, that is, sociomaterial (Orlikowski and Scott 2008). This insight is arguably not new, and has been found to be influenced by works such as actor-network theory (Latour 2005), and Law's concept of relational materiality (Law and Mol 1995). Sociomateriality then continues in the tradition of science and technology studies, that has demonstrated empirically the "*constitutive entanglement of use/ technology"* (Monteiro et al. 2012a, p. 93). Recent studies have shown how technologically enabled representations are actually the result of empirically driven representational practices rather than passive readings of sensors (Almklov and Hepsø 2011; Østerlie et al. 2012). This symmetrical practice is also central in capability design thinking: "*No single dimension is more important than another. One may be easier to achieve, e.g., it may be easier to deploy technology than to change culture, but both are required for success. This is a critical concept because value arises from the synergy of the four dimensions, not the singular effect of each individual one. A debate over the relative value of people versus technology misses the point that both are required and can needlessly side-track the transformation effort*." (Henderson et al. 2013, p. 5) How this imbrication is best practiced, is not known a priori. Ciborra explains how we need to design to enable a flexible *bricolage*, which is characterized by; "*flexibility, movement and transformation obtained from intersecting, penetrating and collating different organizational arrangements, such as the network, the matrix, and even the hierarchy*." (Ciborra 1996, p. 104)

In the cases presented above we have also shown how tensions are dealt with by exercising considerable flexibility. We find that flexibility takes the shape of two capabilities that involve the social and the material: *convergence* and *maintenance*. We consider these to be sociomaterial capabilities, since they require flexibility from both the organization and the technology, or the social and material. The flexibility must always be performed, but also continuously developed; "*The central dynamic driving in this transformation is the process wherein digital technologies, physical phenomena, and work processes for monitoring and controlling these phenomena evolve together in continuous interplay*" (Østerlie 2012, p. 108). Designers of information systems should therefore pay consideration to the "*continuous interplay*". Different scholars have addressed it using different names. Starting from a capability viewpoint, Henderson et al. (2013) explain how we should build "...

on a view that a capability platform is an information ecology, the dynamic nature of capabilities allow for innovation emerging from these capabilities. Technology in a capability platform is an enabling device for people, processes and governance" (p.4). Anderson (1999) argues that such organisations are far from equilibrium; "*Adaptation is the passage of an organization through an endless series of organizational microstates that emerge from local interactions among agents trying to improve their local payoffs.*" (p. 228) Information infrastructure research explain the evolutionary dynamics of information infrastructures by drawing upon complex-adaptive systems theory (Hanseth and Lyytinen 2010). Their approach is relevant in terms of showing how distributed, large-scale information infrastructures like those for oil and gas unfold and self-organise, in spite of the apparent lack of standardized data management system or the major constraints imposed by the local contexts, as shown in the previous section. To design for sociomaterial capabilities means to consider and contain the tensions existing between the global and the local (through convergence), and the formal and dynamic (through maintenance).

First, convergence is a concept used by Bowker and Star (1999) in science and technology studies, to label the result of the ever local, ever partial sequence of translations within infrastructures, as a co-construction of nature (corals, fish, rocks) and society (the oil and gas business, authorities). Social, political, and economic interests are embedded into the bricolage work of modelling subsea environmental risk. Convergence is the capability to leverage the performative aspects of operations in order to overcome the dichotomy between the local context (presence of corals with given characteristics in an area) and the global corporate infrastructure with its formal requirements and work processes. Indeed, our cases show how the "location" has the same sociomaterial properties of the infrastructure, in the sense that it stretches across space (subsea and onshore) and time (real-time data to inform long-term environmental monitoring). According to Monteiro et al. (2012b): "*Work practices are local in the sense of being shaped by local social, historical and material circumstances but not local in the sense of being confined in time and space to a particular locale*." (p. 171) As illustrated above, real-time environmental monitoring today implies finding situated, temporary, and ad hoc – in a word, *performed* – heuristics to fit the institutional requirements and, at the same time, the need for a more cross-organizational infrastructure.

The second sociomaterial capability, identified from the case of oil and gas exploration, is *maintenance*. Maintenance is all the often invisible work (Star and Strauss 1999), done by the many, that seldom comes into the foreground, until something breaks, then it becomes extremely visible and urgently needed. Consider our modern societies and cities, and all the continuous maintenance work that goes into keeping roads, water, electricity up and running. The same is required in sociomaterial capabilities. What many designers arguably get wrong is that they do not have a full picture of the complete set of stakeholders that is needed to have the organization running. Maintenance is often neglected "*But it is in between breakdown and restoration of the practical equilibrium – between the visible (that is, "broken") tool and the concealed tool – that repair and maintenance, makes its bid for significance*" (Graham and Thrift 2007, p. 3). In oil and gas exploration, it is, as we have shown above, not just the ingenious geologist that strikes oil, but also less visible work of the unsung maintainers that keep the nuts and bolts going.

Below, drawing on and extending information infrastructure work, we give some design implications of this insight.

4.2 Design principles for Convergence and Maintenance

IS designers should *opt for value-driven design* (I)**.** This principle is about allowing scalability of local phenomena. Doing so can help overcome the bootstrap problem encountered by early adopters of a new system, when costs and risks outnumber the actual benefits (Hanseth and Lyytinen 2010). The need to design for direct value has also been advocated for engineering data representations and models, like ontologies that have been very popular in the last decade. Data models are an integral part of the standardization of cross-organisational infrastructures, but often present underestimated challenges at the level of the local implementation (Hepp 2008). A capability platform thinking (Henderson et al. 2013) suggests overcoming this paradox by fostering an infrastructure's scalability and at the same time focusing on the local value. The EnviroTime case showed how the discrepancies at the local level would not allow the creation of a fixed and overall representation applicable to every operational field for environmental monitoring. Central and local decision-making must converge into something considered as valuable, for instance to decide how many parameters are actually needed and at which resolution to track fish: "*Because one of the big discussions we have had in the project is 'Ok, so what are the* *data, what kind of decisions are the collected data serving?' Because if you do not have any actions you can do, then one can raise the question: 'Is there a value of the data at all having real-time data if you are not making decisions on it?'"* (Environmental advisor, interview 2013) As the infrastructure is being built around real-time environmental monitoring, the social and natural worlds are necessarily inscribed into it. How much of these worlds is in fact a bootstrapping operation (Bowker and Star 1999), where part of the work of convergence is done by splitting the worlds into useful categories. Will you need to track all the 5 dimensions about a fish at a high time granularity? Or will these more complex data be mirrored by the availability of algorithms to properly analyse them? Or maybe for the sake of getting a long-term trend of the fish's behaviour it is enough to know their concentration in few points of the water column, say, every hour?

As stated above, the development of new information infrastructures within the oil and gas upstream sector is never a tabula rasa. A second principle is therefore to build upon the information *legacy* (II), or installed base. The EnviroTime project is an illuminating case of this requirement. NorthOil being a 40-year-old energy company, it owns a distributed infrastructure for its daily operations, made of pipelines, cabled or wireless data transfer systems, devices, subsea or traditional installations, and, equally important, practices, regulations, and professional knowledge. For example, more than 30000 formal work processes are stored in the corporate databases. The work processes must now be complemented or modified to account for the flow of real-time environmental data that must be coupled with the flow operational data (e.g. exploration, drilling, production). But the necessary technology can be missing – as is for instance the case of the exploration phase, where no investment can be made to install permanent equipment as there is no certainty for profit yet – thus demanding the organisation to reconfigure its capabilities to the new reality, and possibly create new ones. In the example above on the tests done by NorthOil, no physical infrastructure was in place yet, so temporary solutions (buoy, satellite connection) had to be deployed. When that equipment was lost, the traditional installed base was leveraged by adapting the existing capabilities (modelling systems, operators' knowledge) to successfully perform the monitoring activity. The way environmental and technical capabilities get combined is often not possible to foresee a priori and depends on emerging conditions.

The third principle is to *account for multiple levels of materiality* (III). Finding information and taking decisions in the oil and gas business combines several levels of materiality. Sensors for instance take an active role in shaping a reality that cannot be directly accessible to humans (Østerlie et al. 2012). That is also true for the data models or the simulation models that re-combine sensor data to represent or predict reality based on specific parameters, as it happens in climate science (Edwards 1999). Strong currents or vessels might cut off the sensor networks. A well-functioning capability in such a scenario consists in finding a convergence between the materiality of physical properties (failing technology) and the materiality of system intelligence (the models). In the story of NorthOil's tests, when the physical robustness of the buoy failed, the modelling systems came into play to supplement critical missing data from the real world. In NorthOil's tests a surface system could not be decoupled from an efficient real-time onshore modelling system. "*So in that way in places where you have a limitation on the deployment of sensors using modelling is very important because you can predict – based on little information you can predict the spreading of the discharge and you can predict the concentration of particles and the sedimentation on the sea bed. (…)This is a system you have onshore in your office to run this continuously based on input on current and discharge...*" (Environmental advisor, interview, 2012) In addition, the examples we have described in section 3.1 clearly indicate that sociomaterial design must not only include the interaction between the user and the interface and the remote sensors. It should also encompass the way this machinery gets imbricated with another level of materiality: that of nature, which must be recognized its own agency. Convergence therefore means encompassing humans, technology, *and* nature. For instance the robustness of subsea devices should be proven against water currents or challenging weather conditions based on the geographical area. In addition, EnviroTime was motivated by the strong presence of corals offshore Norway, but also the fish living inside the corals should have their say in the system.

Einstein is quoted stating "*Make things as simple as possible, but not simpler*". This is indeed true for a sociomaterial maintenance capability as well. Our fourth design principle (IV) to support sociomaterial maintenance is therefore to *keep it simple*. Although well known, it is far too often forgotten, with subsequent failure. The IS components of a capability must be as simple as possible in order for maintenance work to be possible and cost efficient. "*What makes a collection of IT capabilities simple or complex is a function of its technical complexity as defined by the number of its technical elements, their connections and rate of change*" (Hanseth and Lyytinen 2010, p. 13), quoting (Edwards et al. 2007). We would add also organisation complexity. As we have seen in exploration, with at least 35 different systems, that are themselves complex, it should be stressed that it is not only the "end user", the geologist or geophysicist that must experience simplicity (not to say that they necessarily do). It must also be implemented at the many levels of maintenance, the project data manager, the central data manager, and so forth. In a situation where new layers are added to the information infrastructure, with ever-new functionality, simplicity must cut across layers as a key architectural and design concern. In so doing, the organisation can release an additional benefit of keeping it simple, which has proven more cost effective to explore new designs with small and lean artefacts. In so doing, one can prove value through simple and "*low-cost probes*" (Brown and Eisenhardt 1997). This is central to a capability platform design strategy where the goal is to build option value by utilising existing layers in the platform. Each layer must have clearly defined and shared interfaces with adjacent layers. Often termed standards, the interfaces provide the mechanism to decouple layer and enable independent yet scalable innovation. There may be competing standards although as a layer matures, one or two dominating standard interfaces normally emerge (Henderson et al. 2013, p. 9).

A sociomaterial capability is successful when it enables an organisation to *"link products together over time through rhythmic transition processes from present projects to future ones, creating a relentless pace of change*" (Brown and Eisenhardt 1997, p. 3). As we have seen, oil and gas exploration involves a complex assemblage of information systems, maintainers, and end users. A key task for the maintainers is to apply different kinds of tools to search for, move, and archive data in and between these systems, in effect, linking the products together, enabling the essential flow of data. Our fifth design principle (V) is to ensure modularity and fluidity of "small" data. Modularity is recognised in the infrastructure literature as a key success criterion behind the Internet: "*One reason for the speed of innovation in Internet was its initial modular design (…). The Internet's simple end-to-end architecture, which puts the 'intelligence' into the end nodes, has proven to be a critical for its adaptive growth."* (Hanseth and Lyytinen 2010, p. 14) Modularity, in the data sense, would entail that data can be split apart and transported between those actors needing it. We see this in the empirical material where the GIS experts run SQL queries and use Python scripts on the results to shape the results into something feasible for the G&G to consume and interpret. Ideally perhaps, all data would be collected in one giant database or silo that is easily indexed, queried and accessible for all. As long as this is not the case, and given the nature of flexible work, a practical strategy is to enable information to flow between systems by facilitating the data moving and tinkering work done by the maintainers (or perhaps "bricoleurs" to use Ciborra's terminology (Ciborra 1996)). Standards are key to such an achievement, but standards must also be kept simple and pragmatic. The standardisation must strike a balance between being lean enough to support flexibility, while still rigid enough to avoid chaos (Brown and Eisenhardt 1997). Incentives must be given, or requirements set, to vendors to make their data interoperable and enable data move frictionless between systems.

Last, but not least, the sixth design principle (VI) is *to include all required stakeholders in the design process*. Too often, projects fail because they simply overlook more mundane roles and tools, such as the maintenance workers or the PowerPoint application, and rather focus on an end-user-developer relationship. The sixth design principle then is to bring the seemingly mundane and everyday into the limelight. It is essential to get an understanding of the role they play as mediators and maintainers of data and information. Emergent design processes, such as DevOps (Loukides 2012) are extending the agile movements customer-developer paradigm. Full appreciation of the sociomaterial capability thinking requires extending the notion of the customer, to include all relevant stakeholders, including but not restricted to roles such maintainers. In an oil and gas setting, such as in the EnviroTime project, other stakeholders that are easy to keep out of the design process are "silent" (non-human) stakeholders in terms of nature, such as corals.

5 Concluding remarks

Successful organisations manage to balance the exploitation of existing capabilities and the development of innovative competencies. A capability platform approach seeks to provide a general framework to address this target by emphasizing the dynamic recombination of people, governance issues, work processes, and technologies. Sociomateriality gives a framework to further understand how a capability platform for innovation performs and how to deal with and design for tensions that must be observed when building information system capabilities in organizations.

In this paper, we have observed two sociomaterial capabilities in the upstream oil and gas sector. Based on an extensive empirical research in two different disciplines, subsurface resource exploration and environmental monitoring, we outlined convergence and maintenance as two strategies to contain and possibly overcome global/local and formal/flexible tensions. These sociomaterial capabilities should be seen as the beginning of a sociomaterial capability platform, encompassing evolving configurations of social and material actors performing at different scales. From this understanding we derived six design principles designers should take into account when realizing sociomaterial capabilities for the organisation.

This work is a step to bridge concepts that belong to different disciplines. The notions of convergence and maintenance are not in themselves novel in IS; however, this contribution's aim has been to take an additional step into the performative nature of sociomaterial capabilities. In so doing we have demonstrated how to adopt such a lens to the notions of capability platform, traditionally part of the strategic management literature, bridging it with the IS literature. Practical implications can then be drawn for the designers of information systems. We listed a set of guidelines to address the realization of systems that aim to become an integral part of a possibly highly complex installed base, of which the upstream oil and gas sector is a highly representative case.

The work we have presented should be seen as an on-going empirical activity. Future research should analyse the sociomaterial performativity of the bits of information – the data – that constantly flow across information infrastructures and thus constitute them. Another interesting direction might be to investigate how development process (like agile methods) fit with the sociomaterial insight of information system design.

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Paper IV

Paper 4

The Digital Coral: Infrastructuring Environmental Monitoring

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The digital coral: Infrastructuring environmental monitoring

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Abstract. Technologies for collaboration within the oil and gas industry, which are referred to as Integrated Operations, challenge traditional geographical, disciplinary, and organisational boundaries. Fuelled by the availability of sensor networks, faster data transfer technologies, shared data exchange formats, and collaborative work flows, Integrated Operations entail difficult transformations at the technological, social, and political levels. We describe and discuss the efforts of a Norwegian oil and gas company to develop an information infrastructure for real-time subsea environmental monitoring. This accentuates the ongoing controversy among environmental concerns, fisheries, and the oil and gas industry. Theoretically leaning on infrastructuring and, methodologically, on the concept of infrastructural inversion, our analysis specifically targets the *evolution of emergent infrastructures over time.* We contribute by identifying and discussing two mechanisms detailing the time-dependent dynamics of infrastructuring: (1) *bootstrapping,* which is particularly pronounced in the early stages of infrastructure evolution and involves exploring the feasibility of subsea environmental monitoring methods and devices, and (2) *enactment,* which is increasingly present in the later stages of infrastructure evolution to weave environmental information into the agenda of heterogeneous oil and gas professionals.

Keywords: Integrated Operations; Environmental Monitoring; Information Infrastructure; Infrastructural Inversion; Infrastructuring; Bootstrapping; Enactment

1. Introduction

Lophelia pertusa (Lophelia for short) is a species of cold-water coral that has built aggregations and reefs throughout the world's oceans over the past 9000 years. The seabed along Norway is home to the world's largest population of Lophelia. Lophelia attracts significant attention and is vital for preserving marine ecosystems, including ecosystems in Arctic areas (Fosså et al. 2002). Meanwhile, the oil and gas operations along Norway have gradually expanded into Lophelia habitats. Environmental and fishing concerns are in contrast with the interests of the oil and gas industry (Blanchard et al. 2014; Fosså et al. 2002). Lophelia represents an interesting and vivid *lens* into the broader and politicised situation. We present an ethnographic study of the ongoing efforts of an international oil and gas company (NorthOil, a pseudonym) to design and develop an infrastructure for real-time subsea environmental monitoring.

Real-time environmental monitoring involves developing a comprehensive network of measuring devices, sensors, communication lines, databases and tools for analysing and presenting data. We draw on the expanding stream of infrastructure-influenced studies in CSCW (Jirotka et al. 2013; Pollock and Williams 2010; Star and Ruhleder 1994). These studies mirror the growing focus in CSCW on the large-scale and long-term support for collaboration provided by infrastructures (Ribes and Lee 2010). An infrastructure for real-time environmental monitoring facilitates increased information sharing and collaboration, but it also generates conflict among the stakeholders in NorthOil (environmental advisors, drilling engineers, and production engineers) and external bodies (Norwegian Environmental Agency, marine research institutions, fishery organisations and green activists).

We ask the following: *What is the work that makes a real-time environmental monitoring infrastructure work?* In so doing, we speak of *infrastructuring* as a verb rather than infrastructure as a noun (Bossen and Markussen 2010). Our infrastructure under study is in-the-making. Infrastructuring highlights the ongoing, provisional and contingent work that goes into working infrastructures. Infrastructural *inversion* is similarly intended to unpack the "invisible" work of infrastructures (Bowker and Star 1999; Star 1999). Our analysis specifically targets the *evolution of emergent infrastructures over time.* We contribute by identifying and discussing two mechanisms that detail the time-dependent dynamics of infrastructuring: (1) *bootstrapping,* which is particularly pronounced in the early stages of infrastructure evolution and involves exploring the feasibility of subsea environmental monitoring methods and devices, and (2) *enactment,* which is increasingly present in the later stages of infrastructure evolution to weave environmental information into the agenda of heterogeneous oil and gas professionals.

The remainder of this paper is organised as follows. Section 2 outlines our perspective on infrastructuring, specifically focusing on the time-dependent evolution of infrastructures in which bootstrapping and enactment play a role. Section 3 provides context to our case. Section 4 presents the research method and explains how our constructs (bootstrapping and enactment) are developed in a dialogue between theoretical inspiration and inductive processes. This section also provides some reflections on how we tailored our research strategy to investigate infrastructure. Section 5 presents our findings formatted through the constructs of bootstrapping and enactment. We discuss and draw implications for our understanding of emerging infrastructures in section 6, and section 7 presents our concluding remarks.

2. An infrastructure perspective in CSCW

We adopt an information infrastructure perspective (Karasti et al. 2010; Monteiro et al. 2013; Pollock and Williams 2010). Monteiro et al. (2013, p. 576 emphasis in original) provide the following definition:

> "As a working definition, [information infrastructures] are characterised by *openness* to number and types of users (no fixed notion of 'user'), *interconnections* of numerous

> modules/systems (i.e. multiplicity of purposes, agendas, strategies), dynamically *evolving* portfolios of (an ecosystem of) systems and shaped by an *installed base* of existing systems and practices (thus restricting the scope of design, as traditionally conceived). [Information infrastructures] are also typically stretched across space and time: they are shaped and used across many different locales and endure over long periods (decades rather than years)."

This emphasises how collaborative practices are achieved through collections of – rather than singular – artefacts (ibid). Infrastructure-influenced studies are increasingly visible in CSCW and have been employed in diverse empirical settings, such as healthcare (Bossen and Markussen 2010), cyberinfrastructures (Ribes and Lee 2010), and distributed collective practices (Turner et al. 2006). For the purposes of this paper, there are three particularly relevant aspects of the body of literature with an infrastructure perspective in CSCW: (i) studies of eScience on the collection, curation, sharing, and collaboration around scientific data (tied to our environmental data); (ii) conceptual strategies for unpacking the 'hidden' work of working infrastructures (tied to our aim of analysing 'hidden' work); and (iii) concepts that highlight the time-dependent, dynamic character of evolving infrastructures (tied to our specific focus on 'young' infrastructures in-the-making).

2.1 Infrastructure and eScience

eScience studies in CSCW look specifically at collaboration between different types and/or groups of scientists. This collaboration relies on creating shared, interconnected and interoperable procedures, tools and vocabularies for collectively working with scientific data (Borgman et al. 2012; Edwards et al. 2011; Karasti et al. 2006). A central theme is collaboration within a *heterogeneous* community of scientists. Scientific disciplines employ distinct vocabularies, methodologies, and practices that make frictionless "collaboration" anything but obvious. Borgman et al. (2012) present the complex interdependencies of environmental data sharing between scientific and technical communities. These interdependencies can be buried under tiny elements of complex systems; the definition of 'data' varies significantly across communities. Disciplinary boundaries may be overcome with metadata (data about data). Edwards et al. (2011) address the key role of metadata for scientific interoperability and demonstrates the prerequisite need for supplementary arenas in which scientists can meet, share, and discuss.

In the UK, eScience has focused on interdisciplinary collaboration between scholars in academic areas and in the humanities in particular. De la Flor et al. (2010) report on how infrastructure supports the collaborative practices of classicists to (re)interpret a Roman tablet from the first Century AD. The authors show the integral role of the infrastructure to the classicists' work in the process of retracing the context in which the text was produced.

In sum, eScience studies of environmental data are rare despite the increasing number of portals used by scientists to share environmental and oceanographic data, e.g., the Alaska Ocean Observing System[i], the Marine Explore portal for global ocean data[ii], the SAM-X portal to integrate marine data with the fishing industry and the oil and gas industry[iii], and the Barents Watch portal to the coastal and sea areas of the European High North[iv]. An exception is Edwards (2010), who discusses the 'machinery' (infrastructure) that has made climate change monitoring possible. He reports on the work of climate scientists to re-examine historical records. Infrastructure embodies the difficulty of recovering the contextual information of old datasets and maintains not only interdependences and relationships but also conflicts on several levels.

2.2 Infrastructural inversion and articulation

An important theme in infrastructure-influenced studies of eScience is *infrastructural inversion* (Bowker 1994; Bowker and Star 1999). Bowker and Star (1994) describe infrastructural inversion as a

> "gestalt switch. (…) This inversion is a struggle against the tendency of infrastructure to disappear (except when breaking down). It means learning to look closely at technologies and arrangements that, by design and by habit, tend to fade into the woodwork (sometimes literally!)"

Infrastructural inversion should be recognised as a generalisation of the long-standing concept of "articulation work" in CSCW (Schmidt and Bannon 1992). Both concepts highlight the *constitutive* role of invisible work and the necessary and non-heroic efforts of working-order technologies (Bowers 1994). According to Bowker et al. (2010, p. 99), these concepts consist of "going backstage" (Goffman 1959). One possibility of inverting an infrastructure is when it becomes visible upon breakdown (Bowker and Star 1999). Jackson (2014) proposes to look at this moment of breaking as generative acts to transform material and human order and meaning in infrastructures. An example of an application of infrastructural inversion in CSCW is the study of a distributed network of sensing devices by Mayernik et al. (2013). The initial incompatibilities between sensors and networking equipment were subsequently "unearthed" to enable an alternative configuration with a re-focus on manual data collection and sampling practices.

eScience scholars have determined (either as "inversion" or "articulation") how efforts distributed across time and space establish collective routines for assessing data quality. In addition to the monitoring and maintenance of technical equipment, these studies underscore the social practices involved in ensuring data quality. Ribes and Jackson (2013) show how the practice of collecting water samples from a stream required modification to ensure that the water was sampled upstream rather than downstream to prevent contamination of the data by the person who collects the sample (e.g., dirty boots when wading into the river). Similarly, Vertesi and Dourish (2011) suggest the need to focus on the strong relationship between the context in which data are produced and acquired and the manner in which the data are shared during scientific collaboration.

2.3 Towards grasping the time-dependent evolution of infrastructures: bootstrapping and enactment

Infrastructural inversion forefronts the "invisible" work of infrastructures, which is vital for any critical study of infrastructures. For all its merits, however, it leaves under-specified how, where, and when infrastructural inversion plays out in emergent infrastructures, which is the primary focus of this paper. A related conceptual strategy is that framed by *infrastructuring*. As argued by Bossen and Markussen (2010), "Discussing 'infrastructure' as a noun is not helpful for analytical purposes, as this suppresses the variety of material and non-material components of which it consists, the efforts required for their integration, and the ongoing work required to maintain it" (p.618). Furthermore, Karasti et al. (2006) use "information *infrastructuring*" to emphasise the crucial role of long-term and continuity in complex systems (see also Pipek and Wulf 2009).

Infrastructuring and infrastructural inversion are generic rather than specific in terms of the time-dependent dynamics of emergent infrastructures. There is work in CSCW on the long-term evolution of collaborative infrastructures, focusing on the temporal aspects. For example, Karasti et al. (2010) elaborate two dimensions of infrastructural inversion: space (local vs. global) and time (short- vs. long-term). They discuss how tensions are resolved if the global and the long-term are addressed in local and short-term everyday practices. Thus, infrastructure becomes transparent when the local and the short-term are simultaneously incorporated into future organisational change. They coin 'infrastructure time' to blur the distinction between design, implementation and the use of infrastructure.

The analysis of the time dimension of inversion is particularly important for understanding the infrastructure-in-the-making. We discuss this through two conceptual lenses: bootstrapping and enactment.

In an explicit attempt to address early-stage infrastructure evolution, the concept of *bootstrapping* has been proposed in the literature with a slightly different meaning (Bowker 1994; Hanseth and Lyytinen 2010; Skorve and Aanestad 2010). In Information Systems, Hanseth and Lyytinen (2010) frame the bootstrap problem as a dilemma for infrastructure designers who must, on the one hand, persuade early users to adopt the infrastructure when the user community is almost non-existent. On the other hand, they are required to anticipate the completeness of their solution. Bootstrapping therefore consists of an algorithm to initiate a new infrastructure by creating a critical mass of users when its use is not formally mandated or economically subsidised (Skorve and Aanestad 2010). The premise of the algorithm is to begin with the simplest solution and enrol a few initial users who may gain benefit without a larger network.

Bootstrapping was also used by Bowker (1994) in Science and Technology Studies, grounded on an empirical case of an oil and gas service company that resonates with ours. He presents bootstrapping tied to the necessarily imperfect fit between the map and the territory: "The process to get enough measurements to do good science and enough work on the oil fields to be able to take local measurements" (p. 33). In other words, bootstrapping is the process of resolving local/global tensions by conjuring a set of meaningful parameters from highly situated realities while simultaneously ensuring their inclusion in a global or standardised picture. Our use of bootstrapping leans on Bowker's version. The concept of bootstrapping remains per definition open-ended in Bowker's work. In our subsequent analysis, we build on but extend Bowker's concept of bootstrapping to include more facets of what goes into the making of an infrastructure.

As an infrastructure grows, the locally produced data have to travel across domains, sites, and work processes, where they are made 'real' in the sense that they are given meaning and roles. As Edwards et al. (2011) remark, the travel of data across interfaces (between disciplines or between machines) is one that generates friction and thus consumes energy when information must be turned into a meaningful and relevant format for a heterogeneous audience. We call this phase *enactment*. It is a fundamental moment of infrastructure evolution because infrastructure becomes such only in relation to organisational practice (Star and Ruhleder 1994). Enactment has been used extensively in practice-based theories, in particular, Orlikowski (2000, 2002). Orlikowski (2000) describes enactment as the process of putting technology into practice. Similarly, Orlikowski (2002) analyses the process of organisational knowing as one in which knowledge is enacted daily in people's practices. In sum, her approach to enactment recognises the reciprocally constitutive relationship between knowledge and practices.

While acknowledging commonalities with Orlikowski's definitions, we lean towards the notion provided by Mol (2002) in her study of medical practice: "[L]ike (human) subjects, (natural) objects are framed as part of events that occur and plays that are staged. If an object is real this is because it is part of a practice. It is a reality *enacted.*" (p. 44). She investigates diseases as never isolated from the practices that stage them; their enactment is not only a matter of representational activities but also of several levels of materiality (from the microscopes to the notepads). The actors are intentionally left vague to leave space for the many subjects and objects that get their shape and actuality on the scene during the activities of enactment of a disease (ibid).

3. Case background

3.1 NorthOil and collaborative work

The Norwegian continental shelf (NCS) consists of the section of the European continental shelf that includes the Norwegian territory and encompasses portions of the North Sea, the Norwegian Sea, the Barents Sea, and the Arctic Ocean. Since its inception in 1969, Norway has developed into a robust oil and gas industry with operators, vendors, oil service providers and consultants alongside increasingly stronger governmental bodies. More than 5000 wells have been drilled. The industry represents almost 50% of Norway's exports, approximately 25% of the GNP and approximately 15% of private sector employment. Our case company, NorthOil (a pseudonym), is one of the major operators on the NCS, with more than 20.000 employees in 36 countries.

An estimated 20–25% of the world's unexplored oil and gas resources are located in the Arctic region, which renders them commercially interesting for the oil and gas industry[v]. However, the same areas are particularly vulnerable from an environmental perspective. Decisions on where to allow and where to ban oil activities for environmental reasons are highly and continuously contested. The major part of the Arctic region and parts of the NCS offshore North Norway are currently banned. Environmental activists argue that oil and gas operators are (presently) not able to guarantee the preservation of these sensitive environments (Knol 2011). Our case of NorthOil's efforts to establish an environmental monitoring infrastructure is part of NorthOil's manoeuvring to open areas of the NCS that are currently banned and, at the same time, gather more knowledge about the ecosystem in general and natural variation in particular.

NorthOil has been involved in efforts to improve cross-discipline and cross-distance collaboration for several decades. Historically, NorthOil was organised around the geographical site of the field. This organisation ensured an extensive and practice-based knowledge of the local field. Responding to a more dynamic reality with smaller and short-lived oil fields, NorthOil has invested heavily in communication facilities, such as increasing data transfer bandwidth, standardising data exchange formats, real-time processing and analysis, and integrating desktop video conferencing tools and shared repositories. Over the past two decades, NorthOil has promoted several high-profiled projects to promote collaboration as part of introducing SAP, Lotus Notes, and Microsoft SharedPoint (references supressed for anonymity). Computer-Supported Cooperative Work (CSCW) within oil and gas operations has been referred to as Integrated Operations[vi]. Integrated Operations have significantly challenged previous geographic (e.g., on- vs. offshore), disciplinary (e.g., production vs. reservoir engineers), and organisational (e.g., drilling vs. production) boundaries (Norsk olje og gass 2005; Rosendahl and Hepsø 2013). The transformations in daily operations implied by Integrated Operations are conflictual and difficult (Hepsø 2009). However, fuelled by the significant trend towards unmanned, sensor-based, and remotely operated subsea facilities, offshore oil and gas operations are gradually displacing the roughneck handcraft tradition with an increasingly information-intensive and collaborative mode of working, which warrants a stronger CSCW attention to Integrated Operations.

3.2 Environmental monitoring on the NCS

Oil and gas activities are potentially polluting, e.g., spreading of drill cuttings (rock material removed from a borehole while drilling), drilling mud (chemicals used during drilling to control the pressure in the well) and oil spills/leakages. To receive formal *permission to drill* a new well, oil operators are required to establish environmental monitoring programs to assess the impact of the planned drilling activity. All installations on the NCS are regularly monitored every third year following drilling. Until now, environmental monitoring has been time-consuming and resource-demanding, with the results (i.e., the data) cumbersome to access due to fragmented and poorly integrated repositories. An environmental survey typically requires 9-12 months, from collecting samples of the seafloor, onshore laboratory analysis and producing a report. Surveys are conducted by consultants or third-party organisations to ensure independence of the oil companies. Distributed responsibility for data collection and long-term surveying results in fragmented information across multiple data sources and data formats, significantly hampering the access, sharing, and interpretation of data.

Government regulations leave the details of environmental monitoring under-specified, including what and how to sample. However, government regulations have recently been tightened and now explicitly refer to the water column, the sedimentation, and the seafloor fauna (Miljødirektoratet 2011). In addition to the identification of the environmentally sensitive flora and fauna in an area, the most common parameters in the water column that surveyors consider are oceanographic data (pressure, temperature, and salinity), the direction and speed of the water currents (to predict the dispersion of biomass or drilling discharges), turbidity (the instantaneous concentration of particles in the water column), sedimentation (the long-term accumulation of particles on the sea bed), and visual inspection of given points through pictures and videos.

3.3 Towards real-time environmental monitoring in NorthOil

There are several compounding reasons for NorthOil's interest in establishing the infrastructure for real-time environmental monitoring that we study. First, and as outlined above, the present methods and procedures are inefficient. Second, real-time environmental monitoring is increasingly recognised to have operational (hence commercial) value. The situation with the cold-water coral Lophelia illustrates this. Despite the fishery industry accounting for 30-50% of damage to Lophelia on the NCS (Fosså et al. 2002), there is growing public concern regarding the impact of oil and gas operations (Blanchard et al. 2014). In 2003, the North-Atlantic OSPAR Commission[vii] included Lophelia in its list of threatened species (OSPAR 2008). When NorthOil was recently requested to relocate its planned drilling site, a costly operation, to avoid harming a colony of Lophelia, one environmental advisor recalls, "*[S]o then we needed to do something (…) to find out whether these guys [Lophelia] are sensitive or not for the [drilling] discharges*" (Environmental advisor 1). Third, very little is known about the impact of oil activities on the subsea environment in general and on Lophelia in particular. This fundamental lack of knowledge is a principal reason for banning oil activities in parts of the NCS and the Arctic. Establishing a new infrastructure for environmental monitoring is thus part of a broad endeavour to supplement the existing lack of knowledge "in a systematic, explicit and transparent manner" (Blanchard et al. 2014, p. 319). With this open-ended agenda, NorthOil faced immediate decisions about what aspects of the environment to capture, how to perform measurements, and where to conduct measurements. Our case follows two streams of activities conducted by NorthOil.

The first stream commenced in the mid-2000s to obtain real-time environmental datasets from a small sensor network deployed on the seafloor off the shore of North Norway in an Arctic area where no oil and gas operations are currently allowed. This project is the first example in which NorthOil is proactively positioning itself within the controversies surrounding oil and gas operations. Initially started as a low-profile initiative, the project has gained significant momentum and is used to promote a knowledge-gathering process. This effort involved exploring uncharted terrain to gain experience and to configure sensors and devices for which oil and gas professionals are unfamiliar.

The second stream is a profiled initiative in collaboration with technology vendors and external environmental experts and advisors to establish an infrastructure for real-time environmental monitoring combined with daily oil and gas activities, as envisioned by Integrated Operations. One of the aims was to provide NorthOil users with a geographical information system (GIS)-based web portal with updated risk predictions for the coral reefs and the surrounding marine environment. This GIS portal is primarily targeted to provide drilling engineers with warnings of potential damage to the coral reefs and to aid the environmental coordinator, a role now filled with new responsibilities for monitoring the impact of oil and gas activities on natural resources based on real-time information.

4. Method

4.1 Approach and access

We use case studies as the background for this study. Consistent with the principles for interpretive methods (Klein and Myers 1999), our aim is to understand the motivations, perceptions, and actions of involved groups during everyday activities and routines. Negotiating access to a case is not automatic for oil and gas companies, which is traditionally a fairly secretive business sector.

We present a case study (see timeline in Figure 1) that is based on two initiatives involving NorthOil. Access to our case was dependent on a number of conditions. The third author is employed by NorthOil while holding a part-time academic position. This author introduced the first author, who is principally responsible for the data collection. The first author was granted an office space and was able to gradually recruit other relevant informants. Being a non-native Norwegian speaker, the first author had to learn the language spoken by all project participants prior to and during the first months of our study. As the ability to understand and speak the language improved, access to additional information also improved. The second author has an extended history of research collaboration with NorthOil, including involvement with the ongoing Integrated Operations activities of NorthOil. The authors, particularly the second and the third authors, have a long history of research collaboration.

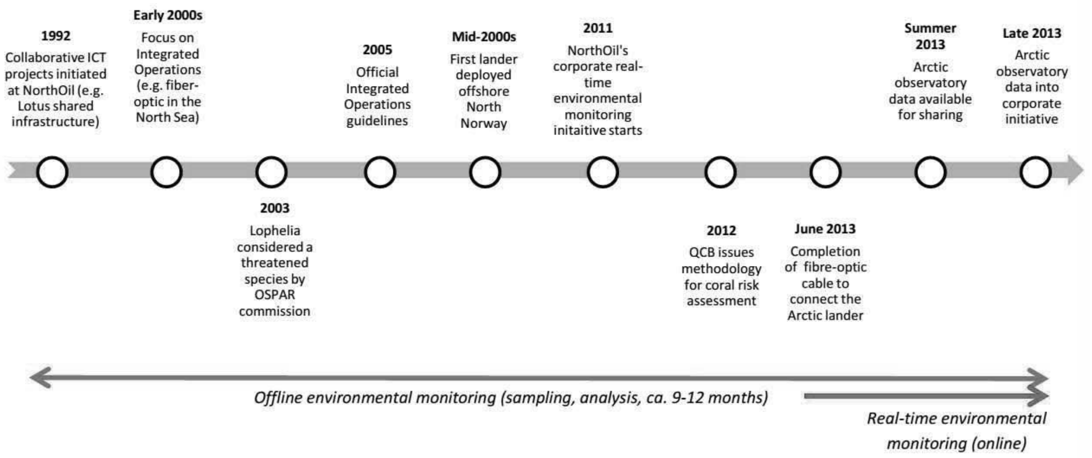


Figure 1. Timeline of the most significant events that led to NorthOil's real-time subsea environmental monitoring initiative and the type (offline, online) of monitoring enabled.

4.2 Data collection

We rely on three modes of data collection: participant observations, interviews, and document study (cf. Table 1).

Participant observations are based on two years of ethnographic observations by the first author. Since April 2012, the first author has been granted access to NorthOil's main research department, where most of the project participants were located. After an initial period in the entrance of the department, this author currently maintains an office space with four project participants. During the two years since April 2012, the first author has spent an average of 2–3 days per week at NorthOil. Data collection from the participant observations was conducted in Norwegian, which is the dominant language used at NorthOil.

The participant observations enabled by co-location provided access to formal project meetings and workshops, as well as informal discussions. They also proved crucial for identifying additional informants to approach. The participant observations provided context for the interviews and document study. In the case of informal conversations over lunch or coffee, subsequent memory-aided transcriptions were conducted as soon as practically possible. Informal conversations, which extended beyond our data collection, were the key to being accepted as a NorthOil 'insider'. For instance, in some meetings, the project members would not always remember that the first author had an academic affiliation rather than a NorthOil affiliation. The third, and occasionally the second, author participated in the meetings and discussions about the projects.

Semi-structured interviews were conducted by the first author, sometimes aided by the second author, at NorthOil's research centre, with occasional meetings at the headquarters of the project partners in other Norwegian cities, to obtain a broader perspective. Informants were selected from NorthOil and gradually from among the partner companies; they were identified during the participant observations or referred by NorthOil employees. For example, 9 interviews were conducted with participants to NorthOil's initiatives from a partner company, Quality Certification Body (QCB, a pseudonym). The informants were professionals with backgrounds in marine biology, environmental chemistry, and corporate IT with different roles. The roles included environmental advisors, project managers, senior researchers, IT advisors, and data-modelling experts. In addition, we interviewed drilling engineers. Informants were coded. We conducted 30 audio-recorded and transcribed interviews (see Table 1). The interviews lasted 1 hour on average and were primarily conducted in English.

Document analysis: We had access to Norwegian and English papers and electronic documents, including email, memos, slide presentations, internal reports, and minutes from meetings. Internal or publicly accessible documentation from NorthOil or competent authorities describing the strategies, plans, and norms were a resource for contextualising the economic and political context in which NorthOil operated during our study. Internal project documentation was a resource for analysing the technical description of the infrastructural components to understand the requirement specifications and the deliveries of the two projects.

Throughout this paper, we will use the term 'project participants' to refer to employees of NorthOil and its partner companies who were directly involved in the two infrastructure initiatives of NorthOil during the phases of infrastructure planning, implementation, and maintenance.

Table 1. A summary of the empirical data and data collection with a description of the covered themes.

Data collection	Extent and theme
Unobtrusive or participatory observations (field notes)	
- Co-location with key informants - NorthOil internal briefing sessions (weekly) - Meetings with other departments - 41 teleconferences (1–6 h) and workshops (1–2 days) with other NorthOil offices and the partners - Informal discussions over lunch or coffee breaks (daily)	- 2–3 days per week for two years (April 2012–April 2014) - General issues - Data management and work processes (every 14 days and on call since autumn 2013; at irregular intervals prior to this date) - Enrolment of users to assume responsibility for the environment - Possibilities and constraints in sensor network configurations
30 Semi–structured and unstructured interviews (transcripts)	

- Real-time environmental monitoring (covered in 29 interviews—9 QCB, 16 NorthOil, and 1 other project partner) - In particular: Arctic ocean observatory (covered in 5 interviews—NorthOil)	- Emerging topics - Environmental monitoring and coral risk assessment - Relations between the NorthOil's initiatives and previous projects - Development of the Arctic observatory - Parallel projects for sensor technology integration
Document analysis	
MS SharePoint team sites (Intranet): - Internal to NorthOil - Shared with partners	- Private emails exchanged during the project - Official reports and deliverables/software specifications - Internal notes and presentations
Internet-based public information	- Official online information about NorthOil and its partners - Official guidelines and reports from the Norwegian Petroleum Directorate[viii] and the Norwegian Environment Agency[ix] - Reports on previous environmental concerns and accidents - Reports from the OSPAR Commission for the protection of the marine environment of the North-East Atlantic[x]

4.3 Reflections on our research method and its scaling

Infrastructure requires suitable scaling methods that are able to account for the balance of action, tools, and the built environment from which it is inseparable (Star 1999). A peculiarity of our case study is that the participants think in terms of a long-term and distributed infrastructure while simultaneously handling daily practical concerns. We considered this point of departure to obtain further access to data and to address the undefined spatial and temporal nature of NorthOil's projects. According to Ribes (2014), to solve this problem, ethnographers, rather than only looking at the large-scale infrastructure, should also ask themselves how the actors on the field look at it: "The key insight in this method is the recognition that anytime there is a 'large' endeavour you will find actors tasked with managing the problems associated with its scale" (p. 158). Thus, the actors can be employed to mediate our access and solve problems of scaling – i.e., for "going backstage" (Goffman 1959). This argument is relevant for us with respect to improving data access. Because the first author was granted a pass to access and freely move in NorthOil's offices in the research centre, she was accepted in the work place and began to identify and shadow key participants involved in different environmental monitoring-related activities. Consequently, we gained access to the Arctic observatory project, which was not initially part of our scope. This approach was also fundamental for addressing distribution. For example, the project partners are located in other Norwegian cities, and conversations have to be established with potential stakeholders in other NorthOil's departments (e.g., the well drilling division), which are located throughout the country. For reasons related to cost and time constrains, one or a few ethnographers could not constantly travel to each of these locations on a weekly basis. We identified a subset of participants in charge of answering the same questions (namely, to find the work to make the infrastructure work) and who needed to cope with large-scale and long-term issues. One example was the way we addressed the concern of merging new routines for environmental monitoring with formal work processes. To mine all work processes used in NorthOil, which exceed 30,000, and to identify the spokespersons of every department in the company to discuss the possible integration of the new routines would have been unfeasible. Due to the good relationship established with several NorthOil employees during the participant observations, the first author was able to 'piggyback' on two of the participants as they performed the work package to enrol NorthOil departments to adapt existing routines. Consequently, we were able to participate in meetings held with department representatives and review and comment on the documentation from these discussions.

4.4 Data analysis

Data analysis was iterative and overlapped with data collection, thus enjoying the added flexibility identified by Eisenhardt (1989). In particular, data analysis was performed in iterations of inductive and deductive steps. Klein and Myers' (1999) principle of dialogical reasoning indeed recognises that the researchers' theoretical commitments necessarily affect the data collection. We interleaved theoretically driven influences by inductively responding to emerging themes from coding of the empirical data (through annotated transcripts, colour schemes, and Post-it notes).

This process resulted in the interpretative template shown in Table 2 with the constructs (i) *bootstrapping* and (ii) *enactment*. These two constructs have a close relationship with the phases of establishing an infrastructure for real-time environmental monitoring. We further specified these two constructs in terms of the underlying *concerns* that we identified inductively. We acknowledge that concerns related to bootstrapping can also surface (and in fact do) at later stages of infrastructure development. However, we conceive of bootstrapping as characterising the early stages of initiating an infrastructure and enactment strategies as being put into practice later on.

To explain the process in greater detail, let us examine how the two constructs emerged.

We were initially deductively attracted by the theoretical concept of infrastructural inversion. We intend it as the articulation efforts over time to create a working infrastructure that has not stabilised and is therefore in the making (Bowker and Star 1999). Infrastructural inversion, however, leaves under-specified the dynamics of the 'young' age of infrastructures. Our informants formulated inversion as *concerns* to find a balance between contrasting requirements. Categorising these concerns iteratively evolved into Table 2. The issues raised by the participants were of course generally not explicitly phrased in terms of concerns (cf. Ribes and Finholt 2009). One example is the need to monitor a "*nice*" coral reef while finding a suitable spot for placing the sensor network. The participants' statements emphasised how the configuration of the equipment played a role in the initiation of the subsea monitoring infrastructure (see concern 'Sensor configuration' in Table 2).

The concerns were situated (e.g., relative to a small portion of the Arctic region) and pragmatic (e.g., by choosing a coral reef that "*was relatively good*" according to the opinion of marine biology experts).

Subsequently, we noticed how comparable concerns re-surfaced when the Arctic observatory was merged with the institutional environmental monitoring initiative in the form of a new scenario that enabled us to reconsider the basic assumptions of the latter ('Scope vs. granularity'). We identified concerns such as "*fish experts… lack experience with reading the [acoustic] sensors from [the sea] floor*" resulting from the current configuration of the sensors in the Arctic observatory. The fish indeed produce different echo patterns when acoustic signals are shot from below rather than their usual position from the top (i.e., from floating fishing vessels). A connection was thus emerging between the making of an infrastructure with global aims and the need to solve very local issues in a pragmatic fashion. Based on this observation, we realised that the concerns could be clustered to specify the concept of bootstrapping. Given the highly exploratory, grounded, and occasionally very serendipitous (see, e.g., the decision to use the Arctic observatory datasets in the corporate initiative) nature of the events described—far from metaphors of design or algorithm—we found Bowker's (1994) concept of bootstrapping to be more suitable to our case than other propositions. The concerns indeed represented an approach to solve local/global tensions by gathering meaningful measurements from situated realities and ensuring their inclusion as parameters in the global infrastructure.

Over time, concerns of a different nature were also being voiced. An explicit aim to sustain the environmental datasets and make them meaningful to oil and gas professionals emerged. First, we inductively isolated statements that expressed concerns related to integrating environmental data management practices with the established oil and gas routines ('*Meshing of new and old*') and to data interpretation ('*Perspective taking'*). Later, we deductively classified these empirical tensions as instances of enactment work. Paraphrasing Mol (2002, p. 44), enactment points to framing the environment on a "stage" that was acceptable for the highly formalised oil and gas domain. We study infrastructure-in-the-making, which, we maintain, is better grasped by Mol's use of the concept of enactment rather than Orlikowski's (2002). By separating the enactment work that is conducted from the initial tensions typical of bootstrapping, we stress two aspects. First, infrastructural inversion has a temporal nature. Our two constructs are thus an attempt to highlight that the time dimension is fundamental to understanding how infrastructures develop and spread. Second, by speaking of a reality being 'enacted', we highlight the importance of the preparation and presentation *work* to be performed to sustain the infrastructure.

Table 2. Our interpretive template reporting the identified phases (constructs) of infrastructuring and the corresponding empirical concerns with excerpt from the field notes.

Construct	Concerns	Excepts
Bootstrapping	Sensor configuration	"*We had to find something with some sort of living coral reef that was flat enough, and we went through a lot of nicer reefs (…) But we had to move away from them because we couldn't find any place for the camera*." (Environmental advisor 3)

		"*Another problem about [the Arctic observatory] is that the fish experts… lack experience with reading the [acoustic] sensors from [the sea] floor*" (Environmental advisor 4)
	Granularity vs. scope	"*[T]he lander or the sensors—they can't see if it's larvae*" (Environmental advisor 4) "*A big fish or a big swimming bladder will return a bigger signal than a smaller one (…)Perhaps that's why we have come up with species with a swimming bladder in this project*" (Environmental advisor 4)
Enactment	Meshing of new and old	"*Our work processes have to be general, not only for the corals since it could only be the case for 1 out of 15 wells that we have to handle.*" (Drilling engineer 1) "*It's the maps that connect it all!*" (Senior researcher 1)
	Perspective taking	"*[T]he link between the sensors for the discharges and the models for the discharges and everything, the link [to say] something about [marine] resources: that's the [coral risk assessment methodology]*" (Environmental advisor 5) "*[For] current measurements, (…) you don't have any electronic transfer; you just gather sediment in a tube and take it off. But if you connect a camera to it, (…) [t]hat's new; it's something nobody has used*" (Environmental advisor 6)

5. Findings

5.1 Bootstrapping

In the summer of 2013, a fibre-optic cable was installed to connect a lander (i.e., an ocean observatory composed of a few networked sensors; cf. Figure 1) on the seafloor of North Norway to a small onshore data centre in a village along the coast of North Norway, in the Arctic region. This Arctic observatory is located at a depth of approximately 250 m and positioned 15–20 km off the coast. The first test results enabled NorthOil to analyse *Lophelia* coral structures in real-time. This prompted discussions about which parameters should be tracked and how.

Figure 2. Left—the process of lowering a lander (source: www.imr.no). Right—a reef of living *Lophelia pertusa* (source: www.mareano.no)

Sensor configuration

The first tension emerged during the positioning of the Arctic lander on the seafloor. The lander was equipped with a camera; sensors to track pressure, temperature, salinity, and turbidity; and an echo sounder (an acoustic device to monitor moving resources). According to one project participant, the lander should be placed in the vicinity of a coral reef that is deemed to be "*as interesting as possible to be put in one photographic frame*" (Environmental advisor 3). However, problems of obtaining a suitable trade-off between an "interesting" coral structure to monitor and a "safe" position for the lander soon emerged. Because only one lander was available, only one coral structure could be monitored. The participants in the Arctic observatory received a map that located all "*nice coral reefs*" from a research institution that collaborated with the project. Unfortunately, the map did not report the steepness of the area, where strong currents form many sand hills. The lander needs to be placed on relatively even surface. In addition, the camera had to be positioned to capture a healthy portion of the coral structure, which influenced the selection of the spot:

> "*We had to find something with some sort of living coral reef that was flat enough, and we went through a lot of nicer reefs that … would [have] serve[d] as … much better objects, probably also from a scientific point of view it would be much nicer… But we had to move away from them because we couldn't find any place for the camera.*" (ibid.)

Consequently, every location on the map had to be tested until the lander could be installed to monitor and photograph a coral structure that "*was relatively good*" (ibid.). According to our interviewees, the "goodness" of the data constituted an empirical balance among the number of species that inhabited the coral structure, the condition of the coral, the flat position of the terrain, and the size in reference to the camera frame. The quest for this balance took the shape of an effort to establish a laboratory for collecting real-time data considered acceptable by environmental experts.

One of the deliverables of the larger real-time environmental monitoring initiative was a GIS-based web portal to provide both environmental experts and drilling engineers with real-time environmental data feeds presented in different formats. The implementation was the responsibility of a number of partner vendors, but it experienced delays and lacked real (not merely test) data. Because the Arctic lander had been connected to the shore a few weeks earlier, real-time data were becoming available. The project managers of the large-scale initiative decided some months after to start using these datasets as they were sent to the onshore data centre. The data served to create map layers inside the web portal not only for visualisation purposes but also to develop the analytical tools for modelling and analysing real-time information. What used to be a small laboratory for the hardware technology became the “Arctic laboratory” in NorthOil official documentation. The new scenario caused a bootstrapping tension that was similar to the problem encountered in the early phase of establishing the Arctic observatory. The measurements were never ‘neutral’. This phase demonstrated that the materiality of the sensors and the objects (the fish) coloured the measurements. One tension, for example, emerged in relation to the physical position of the Arctic lander. Corals are static structures on the seafloor; thus, sensors that used to be employed from the sea surface had to be repurposed to be capable of operating from the seafloor. Echo sounders are routinely used in fishing vessels to detect fish. In its simplest configuration, an echo sounder measures the echo produced by an obstacle that encounters its beam, e.g., a fish. NorthOil’s project thus decided to adopt the state-of-the-art exemplar in the Arctic lander to scan a given section of water from the seafloor and track the moving resources in a 3D area of the water column, the size of which is dependent on the configuration of the echo sounder. The assumption was that it could be useful for monitoring the fish and the biomass floating around a coral reef. The measurements from the Arctic lander were collected using the new method: they tracked the echo of the beam that hit the fish’s lower part. However, two problems remained. First, the new bottom-up readings were a new data type for marine biologists involved in the latter project. They had previously experienced echo readings of fish from above rather than from the seabed (i.e., from below). The relationship between the size of a fish and the strength of its echo is dependent on the features of the fish as observed by the echo sounder. For instance, for cod, the strength of the echo measured from above is obtained through an empirically based mathematical formula to convert the echo (measured in decibels) into the size (e.g., centimetres). The corresponding formula for the measurements from below is not available to the participants in NorthOil’s project. As explicitly noted during one workshop, new expertise was required and many experiments needed to be performed to interpret the new data type. Second, this change created incompatibility with the historical data and map layers that were collected by research institutions over the years and that were based on the traditional top-down measurements from boats. To create robust knowledge about baseline environmental conditions, insight into normal variation presupposed a longitudinal perspective because temporal, seasonal, and regional variations were significant.

Granularity vs. scope

An additional concern emerged regarding the limitations of the Arctic sensors contra the ambitions of NorthOil's larger real-time subsea monitoring initiative. The sensors on the lander were indeed limited in scope and type because they were designed for limited use compared to the larger reach required by NorthOil's initiative. Moreover, one of the goals of NorthOil was to obtain measurements that were sufficiently granular to track the drifting of small eggs and larvae of the cod and herrings that spawn in the area following the water current. The assumption was that these organisms are more sensitive to pollution because they cannot react and swim away like fish can. Monitoring fish eggs and larvae was particularly important to the long-term goal of positioning NorthOil vis-à-vis areas presently banned from oil and gas operations. However, due to sensor limitations, the wavelength of the Arctic echo sounders was not small enough to sense the smaller biological resources, particularly in the upper part of the water column. Figure 3 illustrates this finding.

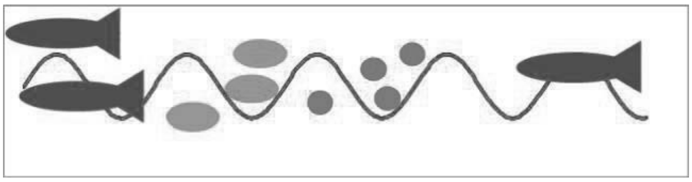


Figure 3. Example of the detection ability of an echo sounder, which is dependent on wavelength (and frequency—e.g., 70 Hz). Fish (e.g., cod, 5–100+ cm) are generally detected, but eggs (1–2 mm, in blue) and zooplankton (1–2 mm, in red) are missed.

Consequently, these types of data were obtained from simulation models that had previously been developed by participating research institutions. These models were based on generic algorithms that describe the drifting of particles that follow the water currents and have been used to simulate the movement of both oil or gas droplets and biomass. To start the model, initial empirical information about the actual presence of biomass was needed, "*You can come up with experience data*" (Environmental advisor 4). The bootstrapping of the modelling practice is dependent on historically layered direct observations of eggs and larvae during a specific period of the year.

To further illustrate this point, consider once again the echo sounder. Fish may respond more clearly to the signal if they have a swim bladder, which is a gas-filled internal organ that contributes to their ability to swim and that also functions as a resonating chamber to receive or emit sounds. As one environmental advisor from QCB explained,

> "*A big fish or a big swim bladder will return a bigger signal than a smaller one (…) Species like the mackerel, which don't have a swim bladder, will return a very small signal. Perhaps that's why we have come up with species with a swim bladder in this project.*" (Environmental advisor 4)

The pragmatic strategy of adopting the Arctic data generated unanticipated consequences for the capabilities of NorthOil's large-scale project, in which participants had to re-configure their expectations vis-à-vis the parameters they planned to monitor. Ideally, the relevant environmental parameters needed for monitoring would be carefully identified prior to devising methods/technologies. Instead, a strategy of improvisation had to be adopted to maximise their use of the resources and opportunities offered by the Arctic observatory. For instance, only fish with swim bladders could be monitored. The forging of the two initially independent projects (the large-scale initiative and the Arctic observatory) demonstrates how bootstrapping tensions re-surfaced over time, albeit in different forms. The need to lower NorthOil's expectations due to the material limitations of the Arctic lander revealed a more basic need to understand the implications of each single sensor for the entire infrastructure. Where technology was insufficient, missing information had to be inferred from a combination of theoretical models and human observations.

5.2 Enactment

The real-time monitoring of the environment in the Arctic observatory was compatible with NorthOil's strong commitment to Integrated Operations and real-time operations. As one industry leader stated, "*[shifting to] real-time operations is the next revolution [in oil and gas]*"[xi]. Still, the new capabilities of environmental monitoring had to mesh with existing routines. Because new methods for *enacting* the subsea environment were needed, these methods had to match NorthOil's existing set of technologies and practices.

Meshing of old and new

The introduction of new data and practices related to environmental monitoring in the installed base of NorthOil took the shape of two concerns on the organisational and technological levels: the adaptation of formal work processes to embrace environmental monitoring practices and the integration of new environmental map layers in the corporate GIS.

Daily operations in an oil and gas company are regulated by an extensive set of corporate-approved and formal work processes. For instance, NorthOil has more than 30,000 formally defined work processes. For real-time environmental monitoring to become part of daily oil and gas operations, it needs to be captured by formal procedures. Thus, new work processes had to be developed and approved, or existing work processes had to be adapted. This situation includes, but is not confined to, the interdisciplinary teams involved in the planning and drilling (drillers, drilling engineers, geologists, and geophysicists) of drilling wells, which are frequently located in the vicinity of vulnerable marine resources; the data engineers who assess the quality of the incoming data; and the environmental coordinators who monitor the impact of operations on subsea biological resources. NorthOil's initiative blurred the distinction between the 'technical' and the 'environmental' tasks. As with general Integrated Operations, a stricter collaboration is necessary between people with environmental expertise (e.g., the environmental coordinator) and people with technical expertise (e.g., the drilling engineers), as the latter may handle environmental information on the same infrastructure: "*[I]n the long run, the technical guys will accept that some of the data [they are fed] is environmentally related. Not necessarily on the same channel but maybe on the same infrastructure*" (Senior researcher 1). Recognising this need for stricter interdisciplinary collaboration, the project embarked on a formal process that was aimed at enrolling and engaging departments that are potentially affected by the availability of new and timely environmental data. This task proved challenging. Some department representatives showed a strong interest in supporting it, whereas other department representatives were more reluctant. For example, NorthOil's well drilling division stated that their work processes were defined and rigid due to strict safety requirements that govern the construction of wells. They maintained that it was not desirable for them to significantly alter their routines. In addition, they noted that coral reefs existed in the vicinity of a minority of wells that they drilled throughout the world; thus, the modifications to work routines could not focus solely on the risk of damaging the corals. The views of the drilling engineers were strongly motivated by their traditional preoccupation with safety in conjunction with the prevention of incidents in technical equipment/systems, as one project member bluntly stated:

> "*[T]here will also be some issues on how you allow [environmental and technical] data to coexist because the technical information has to have priority (...) A coral might wait, a machine won't, so to speak (...). When you are drilling the first top section [of a well], you may have shallow gas, so it's a very [safety-]critical operation, which will take priority*" (Senior researcher 1)

Consequently, NorthOil's project managers decided to enforce the new routines for environmental risk prevention in corporate work processes related to well planning and drilling only upon the detection of vulnerable resources.

As illustrated for drilling, forging new and environmentally oriented work tasks to existing entrenched tasks was challenging. Maps of the seabed environment have been critical to the planning and execution of offshore work. Knowledge of the seabed terrain is critical to properly install moorings and to establish the exact location of the pipelines and subsea equipment to prevent the destruction of infrastructure that has already been installed and is operational. NorthOil already had a sophisticated GIS-based infrastructure for which most of the company's seabed infrastructure was digitally mapped. Critical maps, which existed as map layers, ranged from bathymetry (seabed topology) to subsea infrastructure with pipelines, moorings, and subsea production systems (refer to Figure 4 for an example). The new environmental maps needed to be incorporated as new map layers on the existing bathymetry and physical infrastructure with the correct coordinates. Although it had been possible to view corporate published maps through portal-like interfaces, a corporate intranet that aimed to integrate these maps into one portal was not available. In mid-2013, due to the pressure of NorthOil's real-time environmental monitoring agenda, a corporate intranet initiative gained momentum such that relevant environmental map layers could finally be published on the existing corporate GIS-based infrastructure. According to one project member, "*Maps are the main carrier of information in this project*" and "*It's the maps that connect it all!*" (Senior researcher 1) These statements addressed the significant variety of intended users. Map layers had to be formatted to ensure compatibility with the NorthOil corporate GIS, which describes the operational fields with the technical infrastructure, the rigs, and the pipelines. After several discussions with the technology vendors, the new environmental map layers were developed using the same GIS software engine as NorthOil's native maps.

To summarise, the general concern of integrating new solutions with the existing norms and regulations of NorthOil involved work to balance two different trajectories: a top-down trajectory, based on a more administrative perspective (adapting the work processes), and a bottom-up trajectory, based on a technical starting point (adapting the sensor data to the maps).

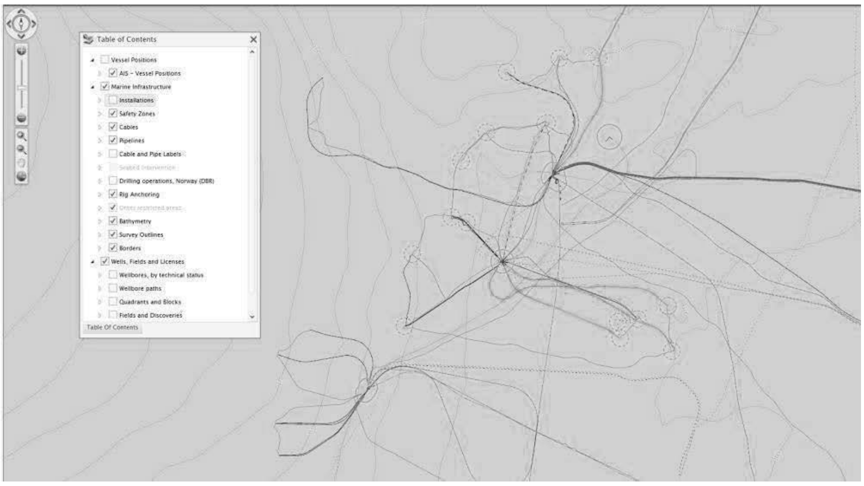


Figure 4. An example of NorthOil's corporate GIS, which displays bathymetric features of the seafloor and the positions of vessels, pipelines, and cables.

Perspective taking

The establishment of environmental data management routines in NorthOil work processes had to be interleaved by engaging the users to help them understand environmental information. Specifying that the biomass concentration at a depth of 250 meters in a GPS location in the North Sea at a given time is "-73.31 dB[xii]" is not very informative for a driller. This issue was addressed by recruiting external experts to interpret environmental information in the context of Integrated

Operations. As acknowledged by one NorthOil environmental advisor during an internal meeting, "*[NorthOil] does not have the internal competence to perform the [environmental] data collection and the data analysis*" (Environmental advisor 1). Environmental data had to be analysed and appropriately presented as meaningful for its diverse users. QCB, which is a reputable, third-party international organisation, enforced the connection between the technically oriented expertise of oil and gas and the expertise of other disciplines.

The process of integrating the map layers described above had to correspond with the process of integrating the adopted language. To facilitate the translation of environmental concerns to (existing) operational work routines, NorthOil's project framed its output in the vocabulary of *risk,* the dominant vocabulary in safety-critical industries, such as oil and gas. This approach was based on an existing risk framework from the guidelines for *coral risk assessment* developed by QCB (with significant experience in environmental monitoring and a history of quality certification and assessment) and issued in 2012 upon the request of the Norwegian Oil and Gas Association. The guidelines describe a number of existing and new routines for gathering data about the location and condition of the corals in an area. Existing data (such as bathymetry) are used and combined with data collected about the corals during subsea remotely operated vehicle (ROV) surveys. During these seabed surveys, QCB's environmental experts would actually name and categorise the corals according to their health condition. QCB's coral-risk assessment methodology, similar to environmental monitoring in general, occurred offline rather than in real-time: "*we give the different habitats a value*" (Environmental advisor 5). This "value" is the result of a combination of technical and environmental information and expertise. It provides an assessment of the condition of coral structures based on the predicted spreading of cuttings during the drilling activity to provide oil and gas companies with recommendations about whether to drill and where to discharge the particles. Only the living portions of Lophelia structures are considered and provided with unique identifiers. Dead coral structures are discarded because they cannot be damaged. An evaluation of the condition of the corals is performed using a colour palette (green, yellow, or red based on the percentage of living corals per total area of the coral structure—refer to Figure 5 top for an example). Environmental data are manually combined with operational information (e.g., the drilling plan), and weather and current forecasts are inputted into predictive modelling systems to simulate and map how the drilling discharges will disperse in the water column and sediment on the seafloor over time. As part of NorthOil's initiative, this QCB's traditional methodology for coral risk assessment was designated as the link between the real-time sensors in NorthOil's (future) subsea observatories, the discharges, and the maps that portray the present and future risk for the coral structures based on tailored integration scripts. As the drilling activity begins, this integration produces an updated picture of potential changes in the impact of the drilling discharges over the coral structures, which are based, for example, on a sudden change of the water current.

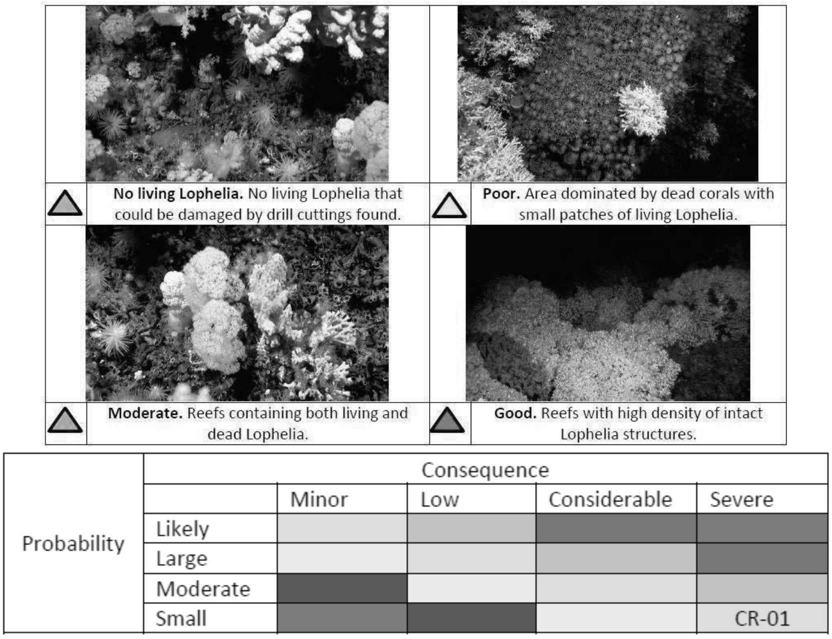
Crucially, the language of risk used to present the environmental information should be compatible with that in use by the professionals of an oil and gas company; at the same time, the risk for the subsea environment that is associated with oil and gas activities should be granted the same consideration as that due to technical problems. This concern was addressed by looking at existing technical solutions and methodologies from a different perspective. First, new combinations of sensors had to provide real-time relevance to parameters that are traditionally monitored offline. Second, methodologies such as the coral risk assessment procedure should be turned into an online machinery to present the risk for the environmental resources using the well-known language of risk matrices.

The first approach consisted of sensor adaptation. The rate at which sediment particles are produced during drilling is not obvious. NorthOil and QCB researchers quickly realised that the existing sensors were not capable of directly measuring the sedimentation and transmitting the results to shore in real time. Although cameras are frequently installed on the landers deployed as part of their "standardised package", they were under-utilised. QCB proposed the idea of installing a sediment trap on one of the test landers to enable pictures to be taken every half hour:

> "*We have sediment traps but... that's just data—you, you don't have any electronic transfer; you just gather sediment in a tube and take it off. (…) But if you connect a camera to it, (…) [t]hat's new; it's something nobody has used*" (Environmental advisor 6)

As a device to simplify the work of image analysis software to detect the actual level of sediment, a contrast black and white background was added behind the trap.

A second solution targeted the way environmental risk was directly displayed to heterogeneous users. It was decided to adopt QCB's methodology of mapping the risk for a given coral reef using a risk matrix (Figure 5 bottom). This mapping was included in the metadata structure that was associated with each coral reef: corals were assigned an identity, a time, a space, a responsible person, and a condition. The metadata structure with the risk matrix included popup windows that appeared as one user clicked the structure on the GIS web portal. Generally, matrices that describe risk are a well-established tool in risk-assessment methodologies. The matrix was put into use twice: to portray the current conditions of corals prior to any drilling activities and to predict the impact during and after drilling. The matrix generated by QCB consisted of a simple 4×4 table, in which the expected probability of pollution was indicated on the y-axis and its consequence was indicated on the x-axis. Each cell was filled with intuitive colours (green, yellow, orange, and red) to signal the level of danger associated with each situation (e.g., low or considerable). The state of risk for a given coral structure was pinpointed in one of the cells for the calculated current pollution and the estimated future pollution.



No living Lophelia. No living Lophelia that could be damaged by drill cuttings found.

Poor. Area dominated by dead corals with small patches of living Lophelia.

Moderate. Reefs containing both living and dead Lophelia.

Good. Reefs with high density of intact Lophelia structures.

		Consequence			
		Minor	Low	Considerable	Severe
Probability	Likely				
	Large				
	Moderate				
	Small				CR-01

Figure 5. Top: a reproduction of QCB's process for mapping the condition of some coral structures based on the predicted spreading of drill cuttings. A good condition represents a high risk of pollution, which is denoted by a red triangle (source of pictures: www.mareano.no). Bottom: a reproduction of the "risk matrix" incorporated into the GIS web portal by QCB, in which a severe consequence is predicted for the coral structure labelled "CR-01" against a small probability of being reached by the plume of drill cuttings.

6 Discussion

Information infrastructure (II) studies in CSCW have reiterated how changes occur in punctuated and constrained ways (Hanseth and Lundberg 2001). Driven by our aim "*What is the work that makes a real-time environmental monitoring infrastructure work?*", we reveal the work of infrastructuring, which involves the slow co-evolution of work practices and infrastructures. To highlight the (articulation) work involved, we focus on the process of infrastructuring (transitive verb) rather than the infrastructure (noun) (Bossen and Markussen 2010). The analytic lens of infrastructural inversion is helpful for detailing the process of aligning the evolving environmental monitoring infrastructure with the significant installed base of existing tools, work practices, and professional roles and responsibilities. It is thus relevant for understanding the focus of CSCW, namely through the investigation of how order is constructed in cooperative settings rather than of cooperation per se (Schmidt 2011). The "gestalt switch" involved in infrastructural inversion implies "shifting the emphasis from changes in infrastructural components to changes in infrastructural relations" (Bowker and Star, 1999, p. 99). It remains however, per definition, a generic notion. In this paper, we use it to address the time dimension by conceptualising the articulation efforts to create a working infrastructure that is still in the making. In other words, it allows us to target the evolution of 'young' infrastructures over time.

We operationalise inversion by describing two infrastructuring mechanisms (*bootstrapping* and *enactment*) that are implicated in the establishment of an environmental monitoring infrastructure. They do not represent clear-cut moments; however, this categorisation is heuristically helpful for understanding the unfolding of the infrastructure. These mechanisms are meant to encompass 'mundane' issues of technology development, adoption, and use, in addition to epistemological issues about remote sensing and knowing the submarine environment only through data. In so doing, a connection is drawn between organisational and scientific work. Infrastructural inversion indeed underlines that the first is cardinal to the latter (Bowker 1994; Edwards 2010). For instance, Edwards (2010) performs an inversion to describe how climate science evolved into what it is today. He shows how climate scientists had to make sense on a global scale of poorly standardised datasets through down-to-earth activities of digitising and interpolating the datasets.

Table 3 outlines the temporal unfolding of our empirical case in terms of the different configurations of the two infrastructuring mechanisms. Unlike the interpretive template in Table 2, here, we aim to present a bird's-eye view on the case. We emphasise how the initial subset of players (that we generally refer to as *stakeholders*, i.e., social groups having direct *purposes* in NorthOil's initiative) increases as the infrastructure grows deeper and broader. We represent the increasing breadth and depth of the infrastructure in terms of the *level of entanglement* with NorthOil's installed base and other, initially unrelated, information infrastructures.

When viewed in this way, infrastructural inversion helps to analyse the temporal dimension of infrastructure. However, it is in the long term that infrastructures often fail to emerge. As Ribes and Finolt (2009) demonstrate, infrastructure development interweaves heterogeneous elements that correspond to different temporal scales of infrastructure evolution. Designers of infrastructure-in-the-making may be hindered by short-term design issues that are related to the immediate corporate goals. We previously discussed how the initial choice of an echo sounder of ordinary quality on the Arctic lander subsequently hampered the ability to track small eggs and larvae, as envisioned by NorthOil's large-scale initiative. On the other hand, the choice of an area such as North Norway without oil-related operations and using the type of open planning adopted by NorthOil (e.g., begin with a small solution, let it grow, share the results externally, and see what needs emerge), may be interpreted as a strategy to design for future growth by postponing final decisions. This design strategy is summarised by an environmental advisor from QCB:

> "*So we will do the best out of what's out there and make… how to put it?… the technology ready for having more, more landers, more information, and to create more detailed map layers, and detailed information. But if you have the infrastructure ready, it's ready for doing that*" (Environmental advisor 4).

To “have the infrastructure ready” resonates with the findings by Karasti et al. (2010), who refer to “infrastructure time”: “[A]n infrastructure occurs when here-and-now practices are afforded by temporally extended technology that can be used in an everyday, reliable fashion. Infrastructure becomes transparent when it exists as an accessible, ready-to-hand installed base that enables envisioning future usages.” (p. 400). NorthOil’s case shows that infrastructure can emerge in a corporate setting by initially relying on a limited and small-scale set of commoditised lightweight devices that, despite some adaptations, constitute a “ready-to-hand” and “accessible” installed base involving a limited set of stakeholders with well-defined purposes and a low degree of entanglement with other infrastructures (bootstrapping). The infrastructure is subsequently pragmatically interweaved with the purposes of new stakeholders (e.g., QCB) or new purposes of the initial stakeholders (the drilling personnel), and with other corporate or external installed bases (e.g., the corporate work processes, QCB’s methodology) (enactment).

We will now discuss these phases in greater detail.

Table 3. Unfolding of the main issues in the bootstrapping and enactment phases over time: stakeholders involved, their broad purposes, and the level of entanglement of NorthOil's initiatives with others infrastructures.

Time

	Stakeholders	Purposes	Degree of entanglement
Bootstrapping	NorthOil environmental experts/coordinators	Increased quality and robustness of environmental data monitoring	Existing subsea technologies (data transfer and sensing) Existing experience with environmental monitoring and data analysis (by oil and gas companies and external institutions)
	NorthOil drilling personnel	More efficient drilling activities (e.g., larger operational window)	
	External research institutions	Provide data and knowledge on subsea environmental monitoring	
Enactment	NorthOil environmental experts/coordinators	Addition of environmental monitoring tasks to existing routines and technologies	NorthOil corporate work processes NorthOil corporate map layers QCB coral risk assessment guidelines and methodology Integrated Operations efficiency goals
	NorthOil drilling personnel	Limited modifications to routines	
	QCB	Improvement of own method for coral risk assessment	
	External research institutions	Limit impact of oil and gas operations on the environment	
	Activists	Limit or ban oil and gas operations on the NCS	
	Other existing ocean observatories (e.g., Alaska Ocean Observing System)	Data sharing	

Bootstrapping

Under the umbrella of bootstrapping, we present strategies to explore the practical feasibility of environmental monitoring in areas inaccessible to humans (cf. Helmreich 2009). When presenting the case of the oil and gas service company Schlumberger, Bowker (1994, p. 41) makes a point that is cardinal to our conception: "in order to produce general science, Schlumberger needed to be local and particular". Bootstrapping is a heuristic strategy that takes advantage of the local/global tensions (e.g., dirty measurements at a site vs. clear-cut global parameters) by creating a 'laboratory' through small-scale operations. Being confined, the laboratory leaves small room for error propagation until it is black boxed into general scientific results.

NorthOil's efforts can accordingly be defined as an attempt to create laboratories insofar as they scientifically re-create subsea nature for a collaborative infrastructure in an oil and gas company. As stated by Latour and Woolgar (1986), "Scientific activity is not 'about nature,' it is a fierce fight to *construct* reality. The *laboratory* is the workplace and the set of productive forces, which makes construction possible." (p. 243, emphasis in original)

NorthOil created a laboratory on a very limited portion of the seafloor offshore North Norway. As clear from Table 3, the number of stakeholders was also restricted to a number of key actors with straightforward goals. This limitation of the 'laboratory' was the key that made it more manageable. A small room for error and low complexity were granted by a relatively small dependence on the other infrastructures, which belonged however to the uniform scientific domain of environmental science.

Performing (just) "enough work" in North Norway "to be able to take the local measurements" (Bowker 1994, p. 33) involved the installation of a minimal solution: no operational information but merely the coral and tracking of the surrounding resources using a lander equipped with a few off-the-shelf sensors. The mundane work conducted to "construct reality" was, however, not minimal. Many combinations of terrain-coral-camera were tested before finding a natural spot that "*was relatively good*". In other words, after many trial-and-error steps, the results of the Arctic laboratory could be packed into presentable scientific parameters (see concern 'Sensor configuration' in Table 2).

The relative simplicity of the Arctic observatory has political and economic importance. NorthOil can gain a competitive advantage by establishing an ecological baseline of the area if authorities permit oil and gas operations. This first seed was reinforced by connecting it to a fibre-optic cable to enable the availability of data in real-time and by gathering sufficient data for later analysis. The later corporate initiative, which was more ambitious, also employed a bootstrapping strategy with available data from the Arctic observatory. The materiality of the echo sounders on the Arctic lander was questioned to test their (in)ability to "take local measurements", for example, of eggs and larvae ('Granularity vs. scope'). A temporary solution had to be reached by injecting the results of mathematical models and experience data. The case of fish detection is paradigmatic of how the bootstrapping phase shaped the real-time environmental monitoring infrastructure. Given the features of the Arctic sensors, NorthOil's project could only rely on the detection of fish with a swim bladder. Other commercially relevant species, such as mackerel, were difficult to spot using the given equipment and were therefore ignored. However, for the moment, it was "enough work".

Given the complex political situation around NorthOil's activities offshore North Norway, our case emphasises one aspect of bootstrapping: the need to ensure that the measurements are considered trustworthy. Jirotka et al. (2005) demonstrate that the trustworthiness of a system is not only dependent on an awareness of others' performance but also "forms part of the work practices through which artefacts are produced and decisions are made" (p. 376). Therefore, it is important "to attend to the work of making systems 'trustable'" (p. 375). This type of work unfolded on at least three levels. First, the involvement of independent research institutions and third-party organisations (QCB) must be understood as a way to enforce the perception of the neutrality (hence credibility) of NorthOil's result in the eyes of external observers. The Arctic laboratory was created to bridge the conflicting interests of the different communities: the choice to deploy the lander in a geographical position that, on the one hand, was located as far as possible from oil-related activities and, on the other hand, was a strategic point to find "interesting" coral structures and abundant environmental resources in the vicinity. Second, internally to NorthOil, trustworthiness is also conveyed through quantifiable results. The work of building trustworthiness was crucial for the Arctic observatory to gain credibility in relation to subsea environmental monitoring, which is primarily an invisible concern for dominant business areas. NorthOil needed to persuade the other communities in the company to trust the business relevance of its results, which also reflected on the broader-scale initiative. For example, during one internal meeting, the representative of the drilling and well department at NorthOil declared "*[The initiative] must produce reliable and trustworthy data about the environmental impact of the drilling operations to ensure it be taken into consideration as an operational modifier*." (Drilling engineer 1, source: internal documentation) The machinery for creating measurable (parameters of) the environment (thus quantified) enables, as Porter (1996) suggested, these measurements to be fed, distributed, and manipulated in various operationally relevant ways, e.g., through the risk matrix. Embedding quantified environmental measurements into operational decision processes—particularly, risk-related process—increases their business relevance and (internal) trustworthiness: "*To make a difference, [the real-time environmental monitoring] system needs to demonstrate a competitive edge in how to algorithmic[ally] treat collected data. It is the most important basis for the trustworthiness of analysed data.*" (IT advisor 2) Third, our case indicates that trustworthiness also possesses aesthetic or rhetorical qualities, as clear in the decision to monitor a coral that can provide a "*good first impression when you look at the picture*" (Environmental advisor 3). Which coral structure to monitor among the available corals is also considered a part of creating the laboratory. This demonstrates that the bootstrapping strategy began prior to the installation of the lander. *Lophelia pertusa* was selected as the focus of NorthOil's projects and – before that – QCB's risk assessment methodology for three reasons. In addition to being highly concentrated on the NCS, coral reefs possess a certain public appeal. As Bowker (2000) notes, "[T]here are certain kinds of plants, animals and systems which are charismatic" (p.655), and those species are more likely to receive the attention of policy makers and research funding for studying their protection. In addition, the coral reefs are a convenient "scaling tool": by inspecting one coral with one static lander, NorthOil would also inspect all surrounding marine resources (e.g., fish, sponges, and crustaceans). This finding also reflects the political connotation of infrastructural inversion: it strengthens the company's argument that the risk of pollution for one coral reef can provide an approximation of the risk of affecting several other species; the corals also signify the conditions of the surrounding habitat. The real-time availability and visualisation promote the idea that corals are an important matter "now" and puts forward the perception that NorthOil would be able to protect them from harm.

Enactment

The second mechanism of infrastructuring that we identified—enactment—encompasses the strategies to make Lophelia and its surrounding subsea environment part of work practices within Integrated Operations. Mol (2002) applies this concept to describe the practices to perform diseases that are moulded by material reality as if it was a reality put on stage when necessary. The enactment work therefore describes those instances of infrastructural inversion aimed to make Lophelia and the subsea natural environment part of the daily "stage" of heterogeneous oil and gas professionals. As CSCW has explained (Schmidt and Bannon 1992), the articulation work of establishing an environmental monitoring infrastructure involves new dependencies between previously independent communities—e.g., drillers and environmental coordinators. In this phase, infrastructuring work becomes more complex (refer also to Table 3). We observe that more stakeholders come into play and that their purposes are more demanding. The environmental experts move steps towards the modification of the installed base of other categories (the drilling personnel) that are, in turn, now more defensive of their routines. QCB also enters the stage as the incorporation of its methodology is proposed. The degree of entanglement with other infrastructures accordingly increases and embraces other disciplines (e.g., drilling).

A naturalisation process is triggered, where Lophelia and the surrounding environment are gradually weaved into the fabric of NorthOil. This finding is particularly evident when NorthOil decided whether to develop new work processes or adapt the existing ones ('Meshing of old and new'). First, environmental information—with Lophelia as the representative—is rendered compliant to the corporate-installed base of NorthOil. The first step to enact Lophelia is to personify it by giving it an identity, a history, and a position on a map on the corporate GIS. A fundamental requirement for Lophelia to be naturalised is that it is understood by NorthOil professionals. Consequently, it becomes a number in a risk matrix. Because natural habitats have to be assigned a value (refer to Section 5.2), Lophelia should be described using an operational language that is familiar to oil and gas professionals—i.e., risk. The risk matrix presupposes a form of categorisation (cf. Bowker and Star 1999) to govern the flow of work in assessing environmental risk. The risk matrix's colour scheme (green, yellow, and red) is dependent on the well-known semantic of the traffic signal.

As we have seen, work practices in oil and gas are strictly regulated by formal work processes driven by standards and norms that are frequently established by authorities mostly for safety-related issues. This situation pertained to the professionals involved in the drilling of new wells, who resisted the inclusion of environmental monitoring tasks (also involving collaborating with environmental coordinators) in their existing routines. The participants in the real-time environmental monitoring project responded pragmatically through a flexible strategy and selected a new routine, not as a general requirement but only when triggered by environmentally vulnerable resources. This is an example of the ad-hoc coordination work implied by Mol's (2002) concept of enactment. Infrastructure indeed has different meanings to different groups of practitioners (Star 1999) because it is entangled with their activities and tools. This is the case with the drilling engineers. Consequently, cross-disciplinary environmental work, at least initially, can be "staged" only when strictly required.

Once Lophelia is real and understandable, the risk associated with potential damage to its reefs has to be relevant to the oil and gas users. The oil and gas business must link its expenditures to finding and producing oil or natural gas because the coral reefs are linked to the future, present, or past and to real or potential operations. By assessing Lophelia's *risk*, NorthOil's methodology includes the assignment of a recognisable dimension by making it visible in terms of space and time. However, it is not an absolute space or an absolute time; rather, they refer to conceptualisations of space and time that the oil and gas industry is accustomed to because these constructs match the time of operations.

The problem of rendering environmental knowledge into a risk language relevant to the oil and gas users was addressed as an epistemic issue by recruiting external knowledge in the project, namely, QCB and its well-established methodology for coral risk assessment ('Perspective taking'). This choice indicates how knowledge emerges as the knot that links the sensors and the models (in this case, GIS-based maps) on which pragmatic decisions are made. A principal motivation for NorthOil was the competitive advantage of obtaining a formal "permission to drill". Operators prefer distinct "*yes*" or "*no*" answers to the question "*Is it safe to drill here?*" This case is an example of the entangled and reciprocal relationship between organisational and epistemic work. A significant amount of scientific knowledge about the environment is a prerequisite for the articulation work not only of sensor deployment but also of decision making. Real-time environmental monitoring is a new method of producing knowledge compared with traditional and offline sampling. Consequently, a new epistemic field is emerging as a result of the articulation work of infrastructuring. Thus, changes in infrastructure are technical and also engage changes in norms, beliefs, and practices (Edwards et al. 2013). This finding not only answers unanswered questions but also proposes new questions (ibid.). An example is the repurposing of the subsea camera for the real-time monitoring of the sedimentation level on the seafloor – a parameter that has thus far mostly been measured ex post or by physically retrieving the sediment trap from the seafloor. A technical solution such as turning the camera towards the sediment trap and adding the black and white background behind the trap enabled experts to perform sedimentation monitoring as an online task, thus paving the way to innovative analytical solutions for the field.

7 Conclusion

There is a relative paucity of CSCW studies of industrial settings in general and of oil and gas in particular—exceptions include (Bayerl and Lauche 2010; Haavik 2014; Heyer 2009; Rolland et al. 2006). This lack of studies contrasts with the inclusive and broad agenda that Schmidt and Bannon (1992) have outlined in their inaugural paper of the CSCW journal. Collaborative tools and workplace studies within industrial settings—e.g., manufacturing, energy, and process industries—have a distinct relevance to the field of CSCW but are under-represented (Schmidt 2011). Our study targets infrastructures, as well as supporting collaboration, that are in-the-making. This is particularly pertinent because our infrastructure under study, on subsea environmental monitoring, is both uncharted and potentially conflictual.

The controversies surrounding oil and gas operations—such as how to balance environmental concerns, sustainable fishing, and industrial activities—are extensive. The outcome remains undetermined. However, both political and operational decisions will depend significantly on “knowledge” about the environment. As our account of Lophelia illustrates, this knowledge is inconceivable without a facilitating information infrastructure to select, collect (measure), analyse, and present environmental data. An environmental monitoring infrastructure does not passively “capture” data. Infrastructur*ing*—the ongoing trade-offs involving measurement accuracy vs. scope, price vs. performance, and bandwidth vs. location of landers—actively shapes what, where, how, and when data are captured. What we know is accordingly embedded in how (instrument and infrastructure) we know it, exactly what we shed light on in unpacking environmental monitoring infrastructuring.

Endnotes

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[i] aoos.org

[ii] marinexplore.org

[iii] www.epim.no/sam-x

[iv] www.barentswatch.no

[v] Source: The US Geological Survey (USGS), 2008 (http://pubs.usgs.gov/fs/2008/3049/fs2008-3049.pdf)

[vi] Refer to www.norskoljeoggass.no; alternative, industry-sponsored labels include eFields and Intelligent fields.

[vii] www.ospar.org

[viii] www.npd.no

[ix] www.miljodirektoratet.no

[x] www.ospar.org

[xi] Refer to newspaper Energyworld, nr 7, 14 Feb. 2014, p. 56

[xii] The concentration of biomass can be measured with acoustic devices, and the returned values are expressed in decibels (dB).

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Paper V

Paper 5

The Nested Materiality of Environmental Monitoring

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The nested materiality of environmental monitoring

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Abstract. Present knowledge about the marine ecosystem on the Norwegian Continental Shelf towards the Arctic is sparse. These areas are vast, remote and subject to harsh weather conditions. We report from a three-year case study of an ongoing effort for real-time, subsea environmental monitoring by an oil and gas operator. The 'facts' about the subsea environment are anything but neutral; they are intrinsically caught up with the material means by which they are known. The marine ecosystem is monitored through a network of sensors, communication links, visualisation and analysis tools. Our concept of nested materiality draws heavily on perspectives in sociomateriality but highlights (i) the distributed and interconnected infrastructure of the material means (as opposed to artefact-centric) and (ii) in-the-making (as opposed to black-boxed) technology.

Key words: sociomateriality, performativity, environmental monitoring, infrastructure.

1. Introduction

With the 'easy' oil already found, oil and gas operations in high-cost, climatically challenging, offshore locations like the Norwegian Continental Shelf (NCS) are knowledge-intensive. Oil reservoirs on the NCS reside 3 – 5 kilometres below the seabed and are known largely through echogram reflections from hydrophones (i.e., seismics). More than 50% of hydrocarbons on the NCS are produced by unmanned subsea installations placed on the seabed. Operational decisions rely on sensor data streams of pressure, temperatures, choke positions, sand detection, and flow volumes, fed by fibre-optic networks and visualised in onshore control rooms. The necessary 'facts' for safe and efficient operations, then, are anything but neutral: they are intrinsically caught up with their material means (sensors, networks, simulations, visualisation) by which they become known (Latour 1999; Almklov 2008).

This general insight is particularly evident when studying knowledge about a quite new (to the oil and gas sector) domain viz. subsea environmental monitoring. Commercial interests in oil and natural gas are pushing north towards the Arctic, into presently banned areas. Extreme weather conditions and a precarious environment make oil operations highly controversial. A political lifting of the ban hinges on establishing a robust 'knowledge base' (NME 2011). Given the sparse, existing knowledge of the marine ecosystem in and close to the Arctic (Blanchard et al. 2014), our three-year case study reports on NorthOil's (a pseudonym) ongoing efforts to establish a capacity for real-time subsea environmental monitoring. We ask: *how are facts about the subsea environment produced?*

We draw on insights from sociomateriality about the constitutive entanglement of technology, work, and knowledge (Orlikowski and Scott 2008; cf. special issue of MIS Quarterly by Cecez-Kecmanovic et al. 2014; and the Scandinavian Journal of IS by Bratteteig and Verne 2012). We adopt a performative rather than representational approach (Pickering 1992). The material circumstances of how 'facts' are produced are crucial yet often black-boxed (Orlikowski and Scott 2014; Østerlie et al. 2012; Pollock 2012). The capacity for environmental monitoring we study is in-the-making thus provides an occasion to open the black box of how key choices are made: *what* aspects to select (e.g., fish, eggs, water, corals), *how* to measure (e.g., echo sounders, pictures, video), *when* to sample (minutes, hours, days), how to represent and *visualise* (e.g., aggregates, graphs, pictures).

We contribute to the modest but growing stock of studies in sociomateriality demonstrating the performativity (Kallinikos and Tempini 2014; MacKenzie and Millo 2003; Østerlie et al. 2012; Pollock 2012) rather than merely proclaiming it (cf. Cecez-Kecmanovic et al. 2014; Jones 2014). More specifically, our notion of nested materiality highlights performativity as *distributed*, *interconnected,* and *interacting* rather than through any singular artefact or sensor alone; nested materiality demonstrates the general principle of performativity found in sociomateriality within the *infrastructure* for environmental monitoring (Jensen and Winthereik 2013; Monteiro et al. 2013).

2. Perspectives on sociomateriality

2.1 Background and precursors to sociomateriality

The discourse on how to conceptualise technology runs long in information systems research. As a counter-reaction to overly deterministic accounts, the significant discretion for users to appropriate information systems was established decades ago through empirical studies (Barley 1986; Gasser 1986; Kling 1986) as well as theoretical concepts (e.g. the 'situated' nature of action proposed by Suchman (1987), the presence of 'workarounds' by Gasser (1986) and leaning on Giddens' structuration theory as proposed by Orlikowski and Robey (1991) and Walsham (1993)).

In their historical recapitulation, Orlikowski and Scott (2008) describe three, broad categories of approaches: (i) discrete entities (with uni-directional causal effects of technology), (ii) mutually dependent ensembles (with bi-directional relationship), before outlining (iii) sociomaterial assemblages. While (i) come with overly deterministic connotations, Orlikowski and Scott (ibid.) acknowledge the rich source of insights provided by (ii). Especially influential are practice-based perspectives (cf. also Jones 2014).

Practice-based research demonstrates the significant malleability of the use of technology by, in a given context, identifying both intentional and unintentional changes resulting from local appropriation, workarounds, and situated innovation that go into users' enactment of technology (Gherardi 2006; Suchman 1987). The use of information systems, then, is malleable because 'every encounter with technology is temporally and contextually provisional, and thus there is, in every use, always the possibility of a different structure being enacted' (Orlikowski 2000, p. 412). A user, accordingly, has substantial freedom to enact her practices with technology in different ways. This malleability in the use of technology enables us to resolve paradoxical or contradictory empirical findings regarding different outcomes of the same technology: seemingly contradictory outcomes are simply a result of contextual differences (Barley 1986; Robey and Boudreau 1999).

The decisive distinction between the former two approaches and sociomateriality, Orlikowski and Scott (2008, p. 455 emphasis added) point out is that:

> "[sociomateriality] is a move away from focusing on how technologies influence humans, to examining how materiality is intrinsic to everyday activities and identities (...) material means are not so much tools to be used to accomplish some tasks, but *they are constitutive of both activities and identities*".

2.2 The performative turn

As noted further by Orlikowski and Scott (2008, p. 460), "[a] central idea entailed in sociomateriality is the notion of performativity". Performativity is an operationalization of the constitutive entanglement of the material and the social (see also Cecez-Kecmanovic et al. 2014; Jones 2014) But what does this 'performativity' entail?

In a widely cited study of the financial option market, Mackenzie and Millo (2003) explicitly set out to demonstrate the performativity of certain formula (the so-called Black-Scholes model) by showing how its initially descriptive role gradually got replaced by an enacting role when the formula was inscribed in (trading) robots and professional routines. As MacKenzie and Millo (ibid., p. 107, cited in Orlikowski and Scott (2008, p. 461)) note: "Option pricing theory (…) succeeded empirically not because it discovered pre-existing price patterns but because markets changed in ways that made its assumptions more accurate and because the theory was used in arbitrage".

However, despite repeated calls to eliminate the dichotomy between the social and the material (Orlikowski and Scott 2008), "the social almost always seems to take precedence, the material merely affording some social/human intention" (Cecez-Kecmanovic et al. 2014, p. 861). Jones (2014, p. 922) too notes that despite claims of the opposite, actual demonstrations "seem [to be] only selectively recognized in the extant literature". Hence the slogan "materials matter" (cf. Barad 2003) is sometimes exactly that, a slogan. The detailing of *how*, not *that*, materials matter (viz. their performativity) remains under-specified.

However, notable exceptions exist (e.g., Jones 2014; Kallinikos and Tempini 2014; Orlikowski and Scott 2014; Østerlie et al. 2012; Pollock 2012). Based on a case study of TripAdvisor, Orlikowski and Scott (2014) show that the nature of a service at any time and place "reflects the materiality involved in its constitution in practice (e.g., equipment, medial, channels, bodies, buildings, spaces, etc.)" (p. 4 in preprint) Similar to the Black-Scholes model, the algorithms at the hearth of TripAdvisor constantly configure – or materialize – the services by conveying choices about what to exclude or not and what should be left explicit or implicit. On the one hand, by materializing the service, algorithms powerfully shape the practices of user crowds. On the other hand, the user crowd also plays a vital role in producing the content configured by the algorithms.

2.3 Towards nested materiality

Particularly relevant to us are the studies of sociomaterial knowing i.e. demonstrations of performativity specifically targeting the production of 'facts'.

Kallinikos and Tempini (2014) analyse how medical knowledge can be created and organized into new models where social media platforms play a performative role (cf. Treem and Leonardi 2012). Social media platforms are complex technological arrangements where social relations are built and shaped by the computational operations embedded into the systems. The authors draw on the case of a social network for medical research and show how. In this process new 'facts' (viz. new correlations between the life paths of patients thus new knowledge for doctors) are materialized through data manipulations where patients are dynamically linked with other patients via the intermediation of a carefully structured architectural underpinning of the particular social media platform. Essential to medical knowledge production is the specific amalgamation of data architecture and computational capabilities with the user interactions, which mutually constitute each other.

Pollock (2012) studies how industry analysts like Gartner produces 'facts' about the market situation of technology vendors in different business domains. Ranking devices, Pollock demonstrates, are performative and ultimately change market domains through the rankings. The ranking device introduces changes to a market domain so that it fits the ranking produced, quite similar to the Black-Scholes model.

In a study empirically close to ours, Østerlie et al.'s (2012) study how 'facts' about non/presence of sand in the oil and gas stream are produced. Presence of sand may severely damage processing equipment. Østerlie and colleagues' study the monitoring work of petroleum engineers through software applications linked to the sand detection sensors installed along the well path. As the well flow is digitalized and becomes a data stream visualized on monitors, 'facts' about sand result from practices, material arrangements for inspecting phenomena, and the physical characteristics of sand. The authors also show how it is crucial in the engineers' daily work to often proceed backwards and unpack this construction process to detect malfunctions and solve anomalies.

Our study clearly shares deep affinities with these studies of 'fact' production. The notion of nested materiality draws on these studies of sociomaterial knowing but is a vehicle to highlight (i) the *distributed* and *interconnected* performativity of the subsea environmental monitoring infrastructure along a punctuated network of digital devices (as opposed to more artefact-centric focus on Gartner's Magic quadrant device or the sand detector sensor) and (ii) the design choices of environmental monitoring in-the-making (thus by *interacting*, as opposed to technology that is black-boxed for the users).

3. Case setting and method

3.1 Case setting

Oil and gas activity on the NCS has expanded dramatically since its inception more than forty years ago. From a modest start, relying heavily on foreign (notably US) expertise, it is today a dominating industry in Norway employing (directly and indirectly) 10% of the workforce, accounting for 30% of GNP and 50% of net exports. Throughout this period, there have been tensions and conflicts with the traditional fishing industry as well as broader environmental concerns. Presently, the inherent conflicts are actualised by the ongoing controversy over whether to allow oil and gas operations in new areas in the Arctic North. These areas, the oil industry argues, are particularly interesting geologically but are also where the most commercially important fishing takes place. Moreover, the areas have stunning scenery, seeing numerous tourists and have rich environmental ecosystems.

Our case unfolds against this backdrop of heated debate. Our empirical material reports from NorthOil's (a pseudonym for a significant, internationally operating oil and gas operator) ongoing efforts to better position themselves for environmental demands and requirements – still not defined – expected to pertain to possible oil and gas activities in environmentally contested areas in the Arctic North. Given the profound lack of robust knowledge about the status of the environment, NorthOil with collaborators (including research institutions) have embarked on projects including the one we report on that aim at contributing towards a more robust baseline measurement of (selected aspects of) the environment.

3.2 Approach and access to case

We document a case study of the establishment in NorthOil of a knowledge base about the marine ecosystems. This effort is facilitated by the introduction of technologies and methodologies for subsea real-time data collection, transfer, and visualization organized into an infrastructure for environmental monitoring.

In offshore oil and gas operations human physical access to the subsea site is impossible, so interaction is always mediated by digital technologies, varied in content, and distributed in space (not only from subsea to shore but also across different nations) and time (obtaining a baseline of environmental behaviour might require decades). Importantly, the installation of digital technologies is fairly recent and ongoing (Henderson et al. 2013) – a feature that allows us to inquire into the design choices as they are made.

The oil and gas business is traditionally secretive, so access was dependent on a number of pragmatic conditions. Facilitated by a member of our research group who also holds a position as project manager in NorthOil, we were introduced to the company's Norwegian research centre, where the first author could follow an ongoing three-year project (December 2011 - December 2014) to set up an infrastructure for real-time environmental monitoring in collaboration with a number of vendors and project partners. The second author has a history of collaboration with NorthOil.

3.3 Data collection

The collection of empirical data was conducted through an ethnographic method (Ribes 2014). We were granted access to NorthOil research centre in April 2012, where the first author spent on average two to three working days a week until April 2014. Main sources of data generation were: participant observations, interviews, documents, and corporate information systems. In Table 1 is a summary of the data types, their amount, and the topics covered.

-- Table 1 about here --

The first author was given a badge and a desk in a shared office space, where she could follow the ongoing activities, join in meetings, workshops, and teleconferences with the industrial partners. In case circumstances did not allow for note taking, the relevant points were transcribed as soon as possible. The regular presence of the first author in the research field also made it possible to shift from being considered an outsider to one of NorthOil's employees. As acknowledged by Klein and Myers' principle of interaction between researcher and the subjects (1999), the continuous, informal contact let us obtain more and richer kinds of data.

Participant observations were crucial to identify the main informants for collecting semi-structured interviews, also from the partner companies. 33 interviews were conducted lasting on average 1 hour, mostly audio recorded and subsequently transcribed. In 8 cases we had no permission or chance to tape, so notes supplemented the lack of transcription.

We also had access to public and restricted documentation (including email threads, slides, minutes of meetings, reports). Together with interviews, documentation was fundamental to understand the technical characteristics and the setup of the subsea sensors and devices adopted for environmental monitoring. In addition, through the company's intranet, we could look at and (sometimes partially) make use of the same information systems used by the employees, e.g., in-use or test modelling software and web portals to track real-time environmental data. These systems were seen or tested by either the first or both authors during meetings or as access was granted to them. Documentation describing these systems was also retrieved and analysed. Interviews and participant observations constituted a backdrop for the identification and interpretation of internal documentation and systems.

The second author occasionally participated in meetings, interviews, and also had access to restricted documentation.

3.4 Data analysis

Our object of study is NorthOil's ongoing efforts to implement a new infrastructure composed of communication architecture and methods to support real-time subsea environmental monitoring. These efforts involve developing, testing, and integrating a large number of sensors, tools, methodologies, and organisational routines. However, the organisational roles of the end users and the decision gates are only partly clear to NorthOil's employees taking part in the initiative. Envisioned work practices include supporting environmental advisors in deciding when the spawning season in contested areas should be halted. This relies on the ability to capture, format, analyse, and present the concentration of environmental resources in the area (e.g., spawning fish and coral reefs). In addition, online risk analysis for static environmental resources like corals should be provided to drilling engineers when a new oil well is drilled on the NCS. If the discharges are transported too close to corals by the stream, any drilling activity must be stopped immediately. The risk analysis capacities are mostly provided by general-purpose semi-automatic modelling software to simulate the dispersion of particles in the water or to analyse pictures of the marine resources like coral structures. Therefore, our unit of analysis is the early stages of infrastructure design and development that precede adoption by the oil and gas professionals in their daily tasks.

Our data analysis is guided by Klein and Myers' (1999) principles for interpretive research. Data analysis was iterative and interleaving inductive and deductive steps. We began inductively by open coding our field notes, interview transcripts, and documentation in parallel with the data collection. The temporal overlap with data collection was particularly significant with reference to our results. For NorthOil's experts the relationship between marine environmental knowledge and the collection of real-time data sets was highly entangled. Consider the example of fish migrations tracking in the NCS. Traditional fish migrations monitoring is conducted from boats. Using the same devices, NorthOil decided to conduct online monitoring from the seafloor through immobile monitoring station that would grant the collection of consistent datasets. No method, however, was known to NorthOil and its advisors to directly compare the datasets collected with the new method with the historical datasets acquired with the old top-down approach. The underlying reason to the mismatch is that the fish's swim bladder reflects the sensor beams differently when hit from different angles (in this case, from below rather than from above). The causal relationship between results, instruments, and the data translation process (the fact) was thus being explored by NorthOil's project participants themselves. We saw this indeterminacy as an opportunity: it allowed us to see the centrality of the problem of performativity of fact production.

Next, a striking observation in our fieldwork was how the facts (e.g. risk for coral reef) emerging from *distributed* and *interconnected* arrangements of natural elements (e.g., coral structures), sensing devices (e.g., a subsea camera), and risk analysis software (e.g., a particle spreading model). Rather than singular sensors like that above to capture fish bladders, environmental facts emerged through an infrastructure. Our resulting interpretative template (see Table 2) spans three moments along the distributed, interconnected infrastructure from the seafloor ('nature') via operations tied to production and maintenance ('operational site') and, finally, visualisations of environmental risk for users.

-- Table 2 about here --

4. Findings

4.1 Performing nature

Spotting the coral reefs. The seas off the Lofoten islands in the Arctic areas of Norway are currently prohibited to oil and gas operations due to the density and richness of their natural ecosystems. They are in particular inhabited by many cold-water coral reefs and host dense migration and spawning of commercially relevant fish species like cod and herring. In the mid-2000s NorthOil deployed a subsea lander (a semi-conic metallic structure, Figure 1) equipped with a sensor network on the seafloor offshore Arctic Norway. The lander was conveniently placed close to a coral structure inhabited by various marine species. In 2013, the lander was connected to an onshore data centre through a fibre-optic cable and the datasets collected by the sensors can be freely visualized and downloaded on a publicly accessible web portal.

The goal of NorthOil was to gain significant background knowledge about the environmental baseline in the area to show authorities the ability to operate without harming the marine environment, had they opened the area to oil and gas extraction. The Arctic lander is thus a key node for NorthOil to discover a non-operational, unknown area. Moreover, the availability of real-time data provides NorthOil environmental experts with a different lens: the subsea environment feels now closer and visible online. The current lander hosts a few off-the-shelf devices, for example *echo* sounders (acoustic devices able to identify obstacles, e.g. fish, in the water column); sensors to track *oceanographic* parameters (pressure, temperature, salinity); and a *camera* taking pictures every 30 minutes. The position of the lander and the orientation of the sensors are not arbitrary but the result of a long process of testing different approaches. The final position was such that the features of the coral structure could fit well in the camera lens.

This new perspective triggered discussions about the best sensor configuration to capture marine life around the coral reef. Initially installed to monitor the health of one coral structure, the subsea lander proved a valuable tool to also track the fish traffic above and around the coral. In this respect, the role of the echo sounders emerged as very important to differentiate the visible from the invisible. The two following snapshots exemplify that the fish are materialized on the users' desktop as the intersection between their own physical materiality, that of the sensors, and that of the modelling software plugged in to inject the missing datasets.

-- Figure 1 about here –

The swim bladder. Echo sounders send acoustic signals at given time intervals and measure the strength of the echo returned by the obstacle hit by their signal. Their performance depends on a number of parameters, for instance the density of the obstacle. Some fish (e.g., cod) have a dorsal swim bladder, an internal organ which is filled with air and allows the fish to control its buoyancy and to emit and receive sounds (Figure 2). Those fish reflect better the signals and are thus easier to detect. NorthOil and its partners soon realized that the direction of the acoustic signal with respect to the position of the swim bladder affects the interpretation of echo sounder data. Echo sounders are traditionally used by researchers and fishermen to detect fish by peeking downwards from ships or floating monitoring stations. However, NorthOil wanted to collect long-term data series from a static position, so boats were no longer an option. Placing the echo sounders on the seafloor means that the new measurements are instead taken upwards (Figure 3). Although expertise on how to compare and convert older and newer datasets is available to some vendors and research institutions, NorthOil's partners admitted it would require them several years to obtain either enough experience or the historical datasets to interpret the new measurements and relate them to existing knowledge bases.

Adult fish vs. eggs and larvae. The echo sounders installed on the Arctic lander are average commercial devices. Their hardware affects what they can detect because they cannot track objects smaller than their predefined wavelength (e.g., 2-4 cm). It is difficult if not impossible to track fish eggs (e.g., 1-2 mm) and larvae (e.g., 4-15 mm) that drift in the water column surrounding the coral structure (refer to Figure 3 for an illustration). However, given the high fish spawning activity in the area, NorthOil wanted to collect data series regarding the drifting of eggs and larvae. It was therefore decided to infer these data from general-purpose simulation models that work by abstracting larvae and eggs to particles following the water flow. Fish is instead more easily detectable (e.g., 5+ cm), but no models are available today to NorthOil's partners to describe fish movements. An environmental advisor points out:

> "*Each adult fish decides for itself!*"

One of her colleagues is frustrated by this situation, as the environmental experts are bouncing between having sensor data and only relying upon models to fill the gaps left by the missing data:

> "*Fish [are] detectable but we have no models; for larvae we have models but we cannot detect them!*"

-- Figure 2 and 3 about here –

4.2 Performing the site

The conditions that make subsea environmental monitoring possible proved site dependent. An environmental chemist explains that the materialization of a marine ecosystem emerges differently based on situated arrangements of the natural environment and the socio-political conditions of the area:

> "*[Environmental monitoring] needs to be based on the sort of political regime, basically the regulations in the country where you are operating. So maybe in some areas there might be a lot of seals or different species of fish, but if they're not a focus for the country, then you need to consider if this is still something that is relevant to monitor. And in other countries or areas it might be possible that a resource that is not really serving a key role in the ecosystem still has a high focus by the regulators, and that needs to be included. (…) [I]t's really a case-by-case decision*"

The Arctic lander was the only one NorthOil had in an area without operations, but other landers were installed in operational areas. For instance, one was allocated off the coast of Brazil, at a depth of more than 100 meters in an oil field which NorthOil had recently acquired. The sensors installed on the Brazilian lander were the same commodified, off-the-shelf devices used in the Arctic. Nevertheless, according to one environmental expert the construction of the lander and the configuration of the sensors had to "*dramatically change*". That was due not only to the presence of oil and gas activities but also to the characteristics of the Brazilian waters. The following empirical snapshots illustrate that environmental monitoring is performed not only within a specific entanglement of technologies and nature, but also within a broader socio-political background where interests and engagements play an important role.

Different natural resources, different sensors. The environment surrounding the Brazilian installation was quite different from the Arctic one. First of all, whereas coral reefs are very dense in the area around the Arctic lander, calcareous algae are the main inhabitants of the Brazilian oil field. Corals and algae are very different: whereas corals are animals, algae are plants and consequently need light to grow. The discharge of rock particles or the occasional leakages generated during oil and gas operations might increase the cloudiness (or turbidity) of the water. That is a critical problem for algae, as the particle cloud prevents the light from reaching the seafloor. As a result, NorthOil decided to also install a light sensor on the Brazilian lander. Another key difference between corals and algae is that the former can construct 35-meter-tall structures, whereas the latter lay on the seafloor in calcified structures the size of a golf ball (see Figure 4 and Figure 5). The camera used on the Arctic lander was installed on a 2-meter-high satellite crane unit cabled to the main lander. In the Brazilian case, the satellite crane was deemed unnecessary, so the camera was placed directly on the lander closer to the seafloor.

-- Figure 4 and 5 about here –

Corrosion and marine snow. The Brazilian waters are different from those in the Arctic because the former are warmer, more corrosive, and currents are generally much stronger. First, the corrosive effect came as a surprise to NorthOil, which was a rather new player in the region. The first steel lander deployed was in fact severely damaged and sensors failed due to corrosion and short circuits. A new lander made of titan was set out a few months later. This time sensors were better protected inside the lander. Second, the strong currents and the high temperature contribute to produce high density of so-called marine snow, mostly organic particles that are lifted from the seafloor and float by increasing the water turbidity. Marine snow does not reflect the sound waves well and therefore cannot be detected by the echo sounders installed on the Brazilian lander. Hence, workarounds had to be found to distinguish the water cloudiness caused by marine snow from the one generated by the more dangerous drilling discharges. A proposal was made to feed the camera pictures into software able to count the particles in the pictures and measure the amount of marine snow.

Brazil vs. Arctic: Different countries require different focus. The nesting of nature and technologies we have just exemplified is also the result of the socio-political conditions of the location where the nesting takes place. Besides, even if the environmental monitoring machinery had to be reconfigured to fit the Brazilian system, it was made possible by the situated experience NorthOil had acquired in the Arctic.

First, NorthOil had to comply with another very local element: the Brazilian authorities. While Norway is characterized by a tradition of well-established collaboration between authorities and oil and gas companies, there is a "*lack of cooperation between authorities and the industry world [in Brazil]*" (environmental advisor). The legal framework is also different, impacting on the speed of decisions related to drilling permits and approval of environmental monitoring programs. In the words of an environmental advisor:

> "*The biggest problem in Brazil is that they have a completely different set of laws and rules than we are used to [in Norway]. Because every single person (…) in the [Brazilian] authorities is personally responsible for his decisions. So if they make a decision and it turns out that it was not good, they might go to jail.*"

Second, according to the employees of NorthOil directly involved in the Arctic and Brazilian projects the ability to adapt the environmental monitoring machinery to very different locations is the combination of two aspects: the possibility of being out in the field and test the technology, and the collaboration with more experienced research institutions and technology vendors:

> "*It was first of all [the Brazilian project] that gave us the experience because then we were present in the field and we had four [environmental monitoring] campaigns (…) But in [the Arctic] it was the [partners who] brought in the experience and not us. So it was in collaboration that we managed to get to a concept that works better [than the first attempts]*" (ibid.)

4.3 Performing environmental risk

NorthOil's experimentations soon generated space and opportunities to explore different calculations and models of risk for the selected marine resources. The results had to be meaningfully re-presented for heterogeneous but still loosely defined audiences (from the environmental experts to the drilling engineers). However, this was not a straightforward issue. The two examples below highlight the complexity of fitting risk calculation approaches into knowledge production mechanisms.

The biomass indicator. Echo sounders and model-inferred data can be combined to compute the concentration of biomass (e.g., fish, eggs, larvae, and zooplankton) in 3D sections of the water column every few seconds. A typical representation to visualize the measurements is the chromatogram, where data are plotted in time and coloured in different ways based on the amount of biological resources. Chromatograms can be very densely populated with data (Figure 6). They are useful to marine acoustic experts, but their granularity was deemed excessive by the environmental experts involved in NorthOil's project, who wanted to receive the results of environmental trend analysis less frequently (e.g., monthly), mostly due to the configuration of their databases. It was therefore decided to divide the water column into larger cubic sections, each associated with a *biomass indicator t*o summarize the biomass concentration inside the cubic section. The biomass indicator is obtained by collapsing some of the original sections scanned by the echo sounders into a bigger one; measures are given every hour instead of seconds. This simplified representational strategy enhanced not only the storing but also the visualisation of biomass data, moving from more than one million to less than five data entries every hour.

-- Figure 6 about here –

Simulation models are often generic tools and are based on assumptions that cannot fully account for the unpredictability of natural variation. As a result, they sometimes do not match the sensor-based measurements. This is for instance the case when simulation models are adopted to predict the potential pollution caused by well drilling activities. In this case, ad-hoc human intervention proves important to make decisions.

The crater effect. The effects of a planned drilling activity must always be simulated prior to the actual drilling of the new well to understand if the water current will take the drilling discharges close to sensitive resources. In a nutshell, these models are obtained by combining into a map layer the water current forecasts and the detailed drilling plan issued by the operator (see Figure 7). During the actual drilling activity, sensors are used to track some key parameters, for instance the cloudiness of the water column near the biological resources in the vicinity of the discharge point or the height and rate of particle sedimentation. It is however often the case that simulation modelling results do not match the values measured by the sensors: models might either underestimate or overestimate the spreading or deposition of the discharges. As a consequence, environmental advisors must constantly compare and contrast the modelled results and the sensor measurements to understand the reasons for the mismatches and, if possible, validate the models. Studies conducted elsewhere report that a relevant contribution is paid by the formation of cutting piles – called *crater effects*, Figure 8 – in the immediate vicinity of the drilling point (Frost et al. 2014). The craters are caused by the chemical particles in the fluids that are used to accelerate the drilling, but that can cause a faster agglomeration of the rock particles contained in the discharges. Aggregated particles therefore tend to accumulate near the borehole without propagating with the water current. In one case advisors reported how they adjusted the simulations produced by their modelling software thanks to measurements provided by one vendor (Rye and Ditlevsen 2011). Their basic idea is to incorporate the crater effect into the model through a manual workaround. After observing that the results of the simulations were one order of magnitude larger than the measured values, it seemed “a natural choice” (p. 36) for them to apply a reduction factor of 15. The new simulated results showed a “much better correspondence” with the real measurements, but, as reported, there is no theoretical justification or “rational reason behind the choice of 15” (ibid.) to simulate the amount of particles held back in the crater.

-- Figure 7 and 8 about here –

5. Discussion

Drawing on the general tenets of sociomateriality, our analysis engages with the specific issue of sociomaterial knowing i.e. the material circumstances of ‘fact’ building as demonstrated in finance (MacKenzie and Millo 2003), market formation (Pollock 2012), hotel reviewing (Orlikowski and Scott 2014) and petroleum production (Østerlie et al. 2012). Leaning heavily on these studies, our analysis highlights the following two differences that serve to characterise our notion of nested materiality.

First, our qualifier 'nested' in relation to materiality is a vehicle to forefront the actual performativity of fact building. In particular, it looks at it as it is being established, i.e. in a moment of high interaction between users and technologies. Second, nested materiality addresses the distributed, interconnected, and interacting – the infrastructural – qualities of how 'facts' are produced. The different elements (cf. Figure 9) in the subsea environmental infrastructure are recursively and mutually constitutive; they are 'nested'. According to the Merriam-Webster dictionary, "to nest" means: "to fit compactly together or within one another". In real-time environmental monitoring, materiality nests (or is made to fit) along the infrastructure (spanning natural elements; sensing devices; modelling software). These aspects of distribution, interconnection, and interaction are thus an effect of the recursive nature of infrastructures. In our empirical case, recursivity acquires a dual nature: on the one hand, the more levels of technological mediation are added, the more complexity and uncertainties are introduced (Jensen and Winthereik 2013). On the other hand, the ongoing (re-)configurations we observed are generative of new sociomaterial relations thus new opportunities to be explored (Tilson et al. 2010).

Let us now discuss the two characteristics of nested materiality in more detail.

First, we focus on technology in-the-making as opposed to black-boxed technology. This displays how users are also acting as designers and are currently giving a shape to their own infrastructure: they are interacting with it, manipulating it, testing different configurations, and discovering new relationships (e.g., between water composition and corrosivity in Brazil). We are not analysing at real-time environmental monitoring as such, but the work to establish it. Focusing on technology in-the-making makes the experimentation and co-production of facts with the technology evident. In particular, it displays how to identify facts. Clearly, not all facts are equally interesting, but who is to tell which one will be relevant? Ribes and Polk (2015) make a similar comment in his historic study of the measurements, instruments, and protocols used to trace the HIV/AIDS virus. As the causes for HIV/AIDS were not initially known, Ribes and Polk quote one informant stating that "*we were ready to handle just about any cause, as long as it wasn't aliens*." (p. 10) In our case, the open-ended concerns for what constitutes relevant facts are highly disciplined by the constraining effect of making the most of available sensors and equipment as illustrated by the experimentation of exploiting the historic data of cod from sonars in fishing vessels (from the top) supplementing the data captured from the seabed (the bottom). This moment is one of the many in our case study that front-stage the entangled relationship between the infrastructure and human grounded expertise to conduct monitoring remotely. Our informants are aware that experience of the local ecosystem's behaviour over time is the only means to learn to interpret the new sensor readings taken upwards and compare them with those taken downwards.

Our case represents a strong emphasis on the role of the natural elements (e.g., fish, marine snow) that further compounds the challenge of identifying relevant facts. Whereas Pollock (2012) does not underline the way the market domain shapes the ranking devices in turn, in our case nature shapes both the behaviour of sensors and that of representations. Differently from Østerlie et al. (2012)'s work, the types of natural phenomena NorthOil is monitoring exist in some cases independently of the sensors (fish concentrates above the Arctic Circle to spawn anyway, whereas sand cannot jam a well without NorthOil building a well) but need to be turned into something relevant for audiences that did not consider them as a 'fact' before. The participants are constantly reflecting on new combinations of equipment to capture these facts. For instance, the intentionality of fish ("adult fish decides for itself") makes it difficult to predict their location in the water column. In contrast to fish, eggs and larvae passively drift with the ocean streams and thus need additional attention by operators: in case of an oil spill they cannot swim away. However, they are not easily detectable; their movement is inferred from software models which treat them as particles. This catches NorthOil and its advisors between having data but no models (adult fish) or models but no data (fish eggs and larvae). In this latter case nature is significant for being absent.

Second, the fact production in our case is tied to a comprehensive infrastructure, a distributed and interconnected network of sensors, communication links, and tools. Rather than being conveyed through single tools/artefacts (e.g., the market ranking device; TripAdvisor's algorithms), real-time subsea environmental monitoring spans heterogeneous layers of sensors (e.g., echo sounders, subsea cameras, light sensors), desktop systems (e.g., chromatograms, particle counters, biomass indicator, discharge simulation models), and expertise (e.g., marine biology, geology, digital electronics) – see Figure 9. Consider the example of dynamic biomass monitoring (fish, eggs, and larvae) and the calculation of the 'biomass indicator'. There exists no such phenomenon as a biomass concentration in nature. Biomass concentration is a purposeful human construct that is composed by the marine resources captured by the available sensing devices (e.g., adult cod but not cod eggs). Further, the intersection between the natural and the sensing elements (see right-hand side of Figure 9) is then fed into models (e.g., chromatogram). These need to be simplified and filtered to fit the left hand side of figure 9, i.e. the databases and software tools.

-- Figure 9 about here --

Models are recurrently used in marine environmental monitoring to produce sufficient and readable results. However, the materiality of modelling software – which is born to be as generalizable as possible – because of its generality, filters the perception of the subsea ecosystems by the experts in the control room. Human intervention in re-presenting a portion of the subsea that does not correspond to any physical or theoretical construct, as in the case of the 'crater effect', is required when models are made part of a risk assessment practice. The 'facts' are often imprecise yet sufficient for the purpose at hand. In a similar way, Edwards describes the relationship between data and (climate) models as "highly incestuous" (1999, p. 452). Representations do not depict one 'true' nature. Their purpose is rather to inscribe negotiated relationships (e.g., environmental experts and drilling engineers) and allow for knowledge to travel and be reproduced, for example to present readable results to authorities.

Our case displays a distributional variability that is not as visible in other contributions, both in terms of distance between the artefacts but also in terms of geography. Our informants spoke of "dramatically" changing the lander and reconfiguring the sensors installed in Brazil. What is done to track coral reefs in the Arctic cannot be the same as for calcareous algae in Brazil. The materiality of these creatures makes them very different. In addition, NorthOil experts had to learn about the Brazilian negotiations, quite different from those in Norway driven by political (e.g., opening the areas off North Norway) and economic (e.g., finding more subsurface resources) reasons. Therefore, the monitoring activities in heterogeneous settings are adapted and linked through the professionals' experience of the different physical conditions as well as of the socio-political ones.

6. Conclusions

Facts about the Arctic marine ecosystem are produced, not given. As our case of real-time subsea environmental monitoring demonstrates, *what* fact is known is invariably tied up with *how* the fact is known. Responding to the recognised under-specification of the programmatic slogan that "matter matters" (Barad 2003), our analysis makes the clear the material circumstances of 'facts'. These facts are key in deciding the future of contested, political questions around where, indeed, *if*, oil and gas operations are to operate alongside commercial fishing and environmental concerns.

The environmental impact is difficult to unpack due to the complexities of natural and technological systems (Barry 2013, p. 13). To illustrate, the government of the US in 2012 denied an international oil and gas company permission to drill subsea wells offshore North Alaska. The concluding report motivates the decision by pointing to the unique challenges associated with the Arctic area, the combination of its "environmental and weather conditions, geographical remoteness, social and cultural considerations, and the absence of a fixed infrastructure to support oil and gas activities" (DOI 2013, p. 6). Addressing the interplay between increasingly distributed and interconnected remote technologies with the environmental and social contexts is fundamental to assess the risk related to human activities. This is relevant also in terms of an early definition of responsibilities in the oil and gas industry where (in)action might lead not only to immediate but also long-term environmental damage. Our analysis is helpful in opening the black box of 'facts' to make visible their material making thus fallibility.

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Table 1. Data types collected during the study, temporal extent or quantity, and themes covered.

Data types and extent	Theme
Participatory observations (2-3 days a week * 2 years; field notes; hundreds of pages)	
- In-office co-location with 4 NorthOil employees - Internal briefing sessions - Meetings with other departments - 41 teleconferences (1–6 h) and workshops (1–2 days) with other NorthOil offices and the partners - Informal chats	- Ongoing environmental monitoring projects - Data management and work processes - Stakeholders enrolment - Sensor network configurations
33 semi–structured interviews (25 taped and transcribed, 10-15 pages each; 8 non-taped, 3-5 pages of notes each; avg. duration 1h)	
- 23 NorthOil employees - 10 employees of industrial partners	- Environmental monitoring and risk assessment - Relations between ongoing and previous projects - Arctic and Brazil observatories - Sensor technology integration
Document and corporate software analysis (Field notes; occasional frequency)	
MS SharePoint team sites (Intranet): - Internal to NorthOil - Shared with partners or vendors	- Private emails exchanged during the project - Official reports and deliverables - Internal notes and presentations - Software requirement specifications - Subsea devices technical specifications
Internal information systems	- Corporate Geographical Information System - Test version of environmental risk modelling software - Public web portal for real-time environmental data - Work processes repositories

Table 2. Our interpretive template with three moments of performativity observed during our analysis. For each moment, we provide an empirical illustration drawn from Section 4 and an excerpt from the interviews.

Moment of performativity	Empirical illustration	Excerpts
Nature	The way a coral structure is monitored depends on its health and the fish species it attracts, how it fits the available subsea camera lens, on the even terrain to position the sensor structure so that it would not flip over.	*"[Y]ou are basically looking for something as interesting as possible to put in one photographic frame (…) it would be good if the coral reef could also attract fish species (…). [W]e had the necessity to have a flat position [to prevent the sensor support structure to fall over]".*
The operational site	Environmental monitoring practices are part of local socio-political practices, where the physical materiality of the subsea field gets entangled with interests and normative frameworks.	*"[Environmental monitoring] needs to be based on the sort of political regime, basically the regulations in the country where you are operating."* *"[T]here was a deal of problems [in Brazil] with corrosion and short circuits because the environment in [Brazil] is extremely corrosive. We had not taken that into account."*
Environmental risk	High-level representations of online environmental datasets are generated and manipulated to produce simplified representations of the risk for the targeted resources.	*"These pictures indicate that a large part of the discharge (…) may be "trapped" inside the "crater" of the pile formation (…) This simulation attempted to take into account the "crater effect" (…) The amount of discharge was reduced with a factor of 15 (…) There is no rational reason behind the choice of a factor 15 of the particle matter to be held back in the crater [, it] seems a natural choice."* (Rye and Ditlevsen 2011)

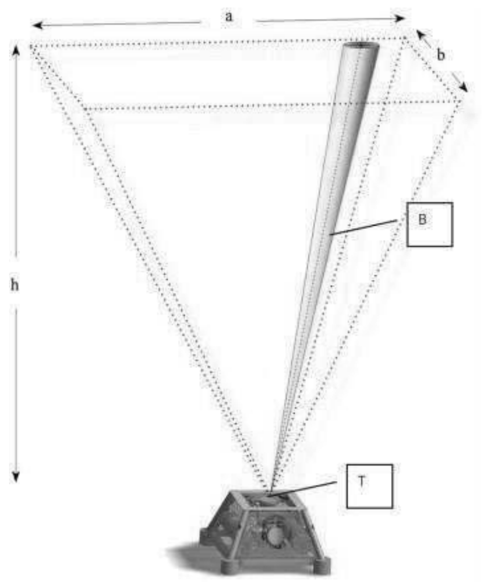

Figure 1. Example of a subsea lander (bottom) and the spanning area of the echo sounders (Source: Godø et al. 2013)

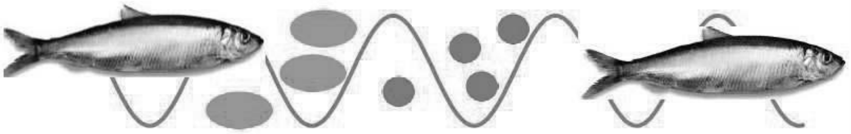

Figure 2. Exaggerated schematic representation of sound wave emitted by an acoustic sensor with reference to the size of adult fish, eggs (blue), and larvae (red).

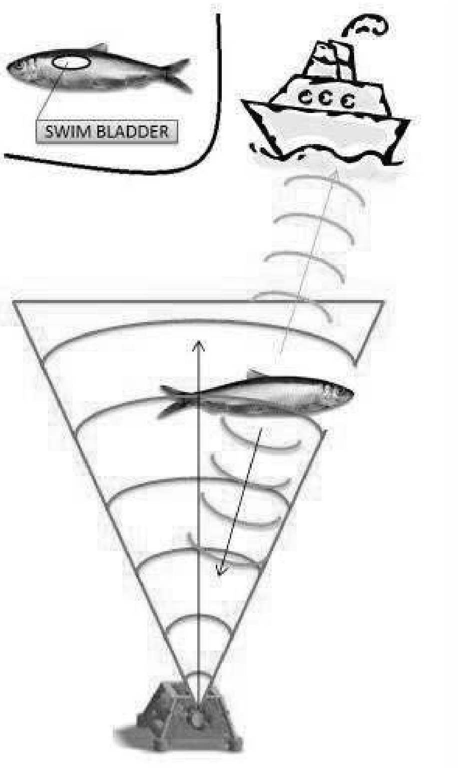

Figure 3. Top, left: position of the swim bladder. Bottom and right: exaggerated schematic representation of the orientation of the echo sounder in Arctic observatory (purple circle) compared to the traditional use from boats.

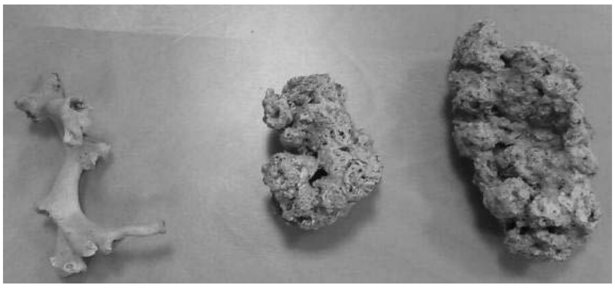

Figure 4. Left, a portion of dead coral; center and right: two portions of dead agglomerates of dead calcareous algae.

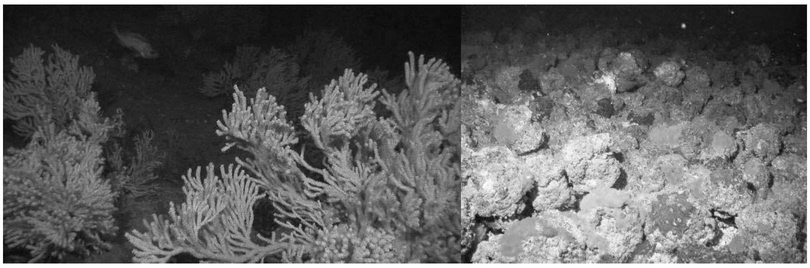

Figure 5. Left: a coral forest (source: http://ww.mareano.no). Right: nodules of calcareous algae (source: http://flowergarden.noaa.gov).

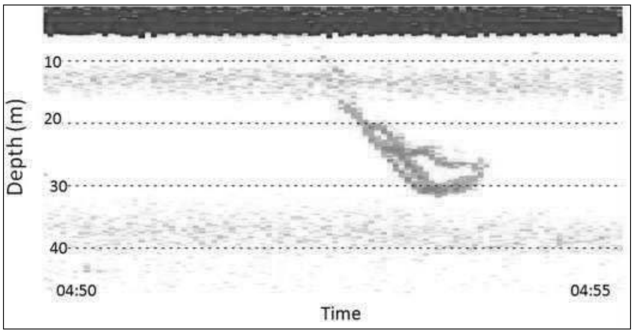

Figure 6. Example of chromatogram (Source: Godø et al. 2013).

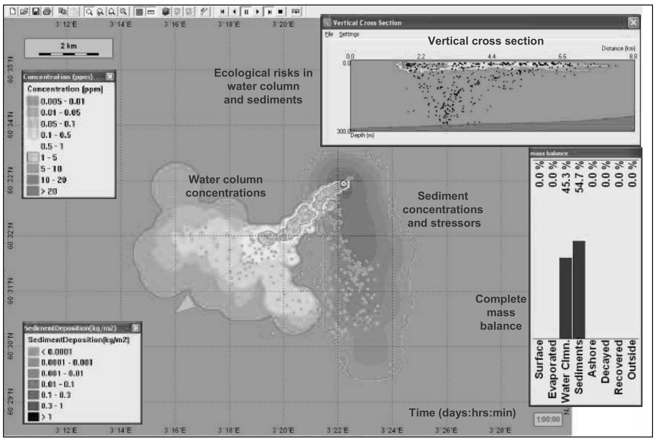

Figure 7. Map of the predicted plume of particles generated during the drilling of a well with reference to the water currents (Source: Rye and Ditlevsen 2011).

Figure 8. The formation of a crated during drilling (Source: Rye and Ditlevsen 2011).

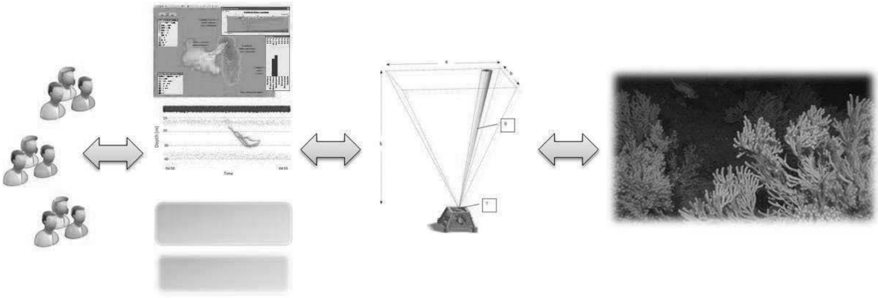

Figure 9. A schematic representation of NorthOil's infrastructure unfolding along a distributed network of digital devices spanning from the seafloor to the users in the control center.

Paper VI

Paper 6

A Measure of 'Environmental Happiness': Infrastructuring Environmental Risk in Offshore Oil and Gas Operation

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SUBMITTED TO: Science & Technology Studies

A measure of ‘environmental happiness’: Infrastructuring environmental risk in offshore oil and gas operations

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Abstract. We present an ethnographic study in an oil and gas company in which an infrastructure was implemented for real-time subsea environmental risk prediction in areas where knowledge about marine ecosystems is rudimentary. In doing so, the company is not only engaged in a process of infrastructuring environmental monitoring systems and practices but is also *infrastructuring environmental risk*.

We identify and discuss three infrastructuring mechanisms: *sensoring*, repurposing acoustic sensors to detect marine biomass; *validating* local measurements against non-existent baselines; and *abstracting*, which assists with embedding environmental risk representations.

We conceptualise infrastructuring as a co-construction of a phenomenon (here: environmental risk) and infrastructures. We demonstrate how this process is moulded through the three mechanisms and how environmental risk becomes a way to articulate spatial and temporal tensions in a politically contested arena.

Finally, we discuss how infrastructure development generates new ways of calculating environmental risk mediated by aspects of materiality and trust.

Keywords: knowledge infrastructures, (socio)materiality, environmental risk

1. INTRODUCTION

> *November 2013. We are sitting in the office of an IT advisor in the research centre of a Norwegian oil and gas company. The advisor is leading the development of a web portal used by the company to display several real-time environmental parameters measured from a subsea observatory that was deployed to the sea floor offshore northern Norway. These data indicate the salinity, temperature, chlorophyll level, pressure, and depth of the water. There is also a graph to represent the biomass concentration in the water column, which is updated every few minutes, and a video made with pictures from the last two days. These pictures are obtained using a camera placed next to a coral reef. When we interview the IT advisor, he has an Internet browser open on one of his two PC screens and an instant messaging program on the other screen. When explaining something to us, he is suddenly distracted by the blinking of the messaging program. One of the programmers working on the web portal wants his attention. The programmer tells him that "the fish is back". The advisor turns to the browser, opens the web portal, and looks at the video frame, where a fish has just appeared in front of the subsea camera. It floats calmly, looking at the camera lens for a while, and finally leaves. The advisor makes a joke and explains us that it is not the first time that fish has behaved in that way. In addition, an analysis of the acoustic measurements indicated that that fish also speaks to the camera:*
>
> *"And that's what happens, he gets really angry. So he says 'Shshshshsh!' (…) Or maybe he gets annoyed. Maybe he gets used to it. And that's also one of the things. Will we [have an] influence? Will the local fauna get used to the sounds when we do the stuff?"* (excerpt from field notes)

Offshore oil and gas operations are contested and subject to heated political and scientific debates that evolve around the risk associated with their possible impact on the subsea natural environment. Scholars have emphasised the epistemological uncertainties related not only to major accidents but also to the long-term effects of routine offshore operations (Blanchard et al. 2014). As highlighted in STS, 'risk' is a constructed, not natural, phenomenon; it is the result of political, economic, and social negotiations (Beck 1992; Jasanoff 1999). Quantifying risk is notoriously challenging because "uncertainty cannot fully be quantified when facing ignorance – what we do not know, and even further: what is beyond our conception of what is possible" (Hauge et al. 2014, p. 87). There are several sources/types of uncertainties regarding environmental risk, namely the difficulty of measuring the baseline environmental state of marine ecosystems, geological and weather conditions, economic or political agendas guiding authorities or companies, and the (non-)availability of technology.

Subsea environmental monitoring practices are not new. These practices have been traditionally conducted by oil companies, consultants (hired by governmental agencies), fishermen, and research institutions. However, these practices are at best fragmented and offline; data are sparsely stored in disconnected data silos with data analysis trailing data collection by months or even years.

We present a longitudinal case study of a Norwegian oil and gas company (NorthOil, a pseudonym) to establish a knowledge infrastructure for real-time subsea environmental monitoring and risk assessment in collaboration with external institutions and vendors. We follow a project to install a real-time environmental ocean observatory in a non-operational Arctic area called Venus (also a pseudonym), in which oil and gas activities are currently forbidden, although the company hopes to gain access to such areas in the future. Because there are no current oil operations at Venus, there is limited knowledge regarding the subsea environment; therefore, there is a pressing need to establish a baseline against which the impact of potential future operations may be assessed. For the newly acquired capacity of NorthOil to conduct real-time environmental monitoring and have organisational uptake, the monitoring system must be embedded in work practices, formal procedures, and tools. This ongoing effort toward environmental monitoring is intended to mimic the way this embedding is performed in an established area, i.e., drilling. Therefore, we also study the real-time monitoring of the technical quality and risk during drilling operations.

Theoretically, our study draws on the growing focus in the STS literature on knowledge infrastructures (Bowker et al. 2010; Edwards 2010; Edwards et al. 2013; Ribes and Lee 2010). Given the centrality of the risk theme in our analysis, we draw connections with ongoing discourses in the literature on the sociology of modernity and risk (Beck 1992; Jasanoff 1999) and marine policy (Blanchard et al. 2014; Hauge et al. 2014; Knol 2013). We ask the following research question: *what dynamics characterise the emergence of a knowledge infrastructure for environmental risk prediction?*

We use 'infrastructuring' (Bossen and Markussen 2010; Pipek and Wulf 2009) to analyse the co-construction of knowledge infrastructure and what we call 'natural' phenomena (the subsea environment and its associated risk). The transitive verb ('-ing') highlights the process aspect of this co-construction (Karasti et al. 2010; Star and Bowker 2002). Based on our findings, *what is being infrastructured is not only the machinery of environmental risk prediction but also the representations of environmental risk perception*.

It is well established in the STS literature that phenomena and infrastructures are co-constructed (Bowker 2000). In this paper, we want to show *how* they become co-constructed through a process of infrastructuring. We do so in two ways. First, we identify the following three constitutive mechanisms: (1) *sensoring*, the bricolage work toward the improvisation and adaptation of acoustic sensors to detect marine biomass; (2) *validating*, the workarounds to ensure that measurements can be trusted and routines can be found to handle them; and (3) *abstracting*, the pragmatic adjustments to make risk representations appropriate to existing routines.

Second, we discuss the spatial and temporal tensions that are triggered by the ambition to make local environmental measurements 'travel', i.e., to have more global significance. These tensions lead to a changed perception of environmental risk, requiring a stronger emphasis on the role of materiality and strategies to enforce trustworthiness in risk assessment in conjunction with social and political accounts.

This paper speaks to both STS and knowledge infrastructure studies. Our core analytical message for the former audience is to emphasise the intrinsically infrastructural and material nature of 'risk'. In this way we are able to discuss the politically charged meaning of facts. Our message for infrastructure studies is thus to draw the attention to infrastructural matters that may otherwise be taken for granted. We seek to avoid essentialist accounts of infrastructure development and show how it rather emerges as continuous two-way oscillation process where local developments generate unanticipated consequences for global contexts, and vice versa.

This paper is organised as follows. Section 2 outlines our theoretical framework by reviewing the literature on knowledge infrastructure, the sociology of risk, and marine policy. Section 3 presents our case study, while Section 4 describes our ethnography-based research method. In Section 5, we present our primary findings based on the three infrastructuring strategies. Section 6 elaborates on the findings and discusses how the infrastructuring process must balance concerns related to generativity, materiality, and trustworthiness. We conclude with a few considerations related to the politics of risk assessment.

2. THEORY

2.1 Knowledge infrastructures and infrastructuring

Pinch and Bijker's (1984) seminal article demonstrated how a constructivist approach to investigating the development of new technologies and scientific facts through empirical studies allows researchers in STS to ask the 'how' questions of knowledge production. Their point remains valid even though STS has moved towards examining larger and more complex artefacts in the last decade, namely infrastructures in which action depends on many interlocking technical systems (Edwards 2010; Vertesi 2014) and ontological questions are emphasised. Knowledge remains socially constructed; however, the 'practice turn’ (Schatzki et al. 2001) has been supplemented by an ‘ontology turn’ that also focuses on material enactments and social interactions (Woolgar and Lezaun 2013).

Knowledge infrastructures (KI), or cyberinfrastructures in e-Science, “comprise robust networks of people, artefacts, and institutions that generate, share and maintain specific knowledge about the human and natural worlds” (Edwards 2010, p. 17). ‘Artefacts’ include information systems (e.g., modelling software and web sites), sensing devices, data transfer technologies and hardware (e.g., subsea equipment). Institutions not only encompass authorities (e.g., national or third-party risk assessment bodies) but also standards and well-established representation conventions.

In their report to the US National Science Foundation, Edwards and colleagues (2013, p. 5) stated that “[i]nfrastructures are not systems, in the sense of fully coherent, deliberately engineered, end-to-end processes. Rather, infrastructures are ecologies or complex adaptive systems; they consist of numerous systems, each with unique origins and goals, which are made to interoperate by means of standards, socket layers, social practices, norms, and individual behaviours that smooth out the connections among them. *This adaptive process is continuous, as individual elements change and new ones are introduced — and it is not necessarily always successful*” (emphasis added). This definition embodies a more system-oriented approach than the relational approach of Star and Ruhleder (1996). Nonetheless, “we ask, *when*—not *what*—is an infrastructure” in both cases (Star and Ruhleder 1996, p. 113 emphasis in original).

Empirical examples of *continuous* KI development originates from several fields, e.g., the petroleum industry (Almklov et al. 2014; Bowker 1994; Østerlie et al. 2012), energy provision (Silvast et al. 2013), climate science (Edwards 2010), medical practice (Jirotka et al. 2005), ecological research (Karasti et al. 2006, 2010), scientific practices (Steinhardt and Jackson 2014), and financial risk calculations (Kaniadakis and Constantinides 2014). On the one hand, these accounts have shown how infrastructure emerges as an ongoing (Karasti et al. 2010) and often fragile accomplishment (Jackson and Buyuktur 2014). On the other hand, they have also emphasised the role of materiality (of hardware and software technologies, datasets, and the physical world) in the process of knowledge production (Almklov et al. 2014; Østerlie et al. 2012; Ribes and Polk 2014; Vertesi 2014).

Interestingly, what many recent accounts have in common is an emphasis on the generative rather than the obdurate nature of infrastructures, which was made clear in a special issue of the Journal of the Association for Information Systems (Grisot et al. 2014; Monteiro et al. 2014) that identified a “coming of age” of infrastructure studies. These findings were echoed by a special issue of the Science & Technology Studies journal on Energy Systems and Infrastructures in Society (Silvast et al. 2013). The uncertainties connected to energy provision and to the promotion of environmental sustainability require the adoption of an infrastructure perspective. Traditional metaphors of systems do not address the long-term orientation of environmental sustainability (and risk) and the continuous balance between expanding size and local usefulness (Silvast et al. 2013, cf. Edwards, 2010).

To embrace the evolving and unstable nature of infrastructures, Star and Bowker (2002) began to use 'infrastructure' as a transitive verb. Thus, the term *infrastructuring* (Bossen and Markussen 2010; Edwards et al. 2013; Karasti et al. 2010; Pipek and Wulf 2009) has been introduced within STS, Computer-Supported Collaborative Work, and Information Systems to mean the strategies of reflexive players (both designers and users) to make complex infrastructures flexible to meet tensions and future problems. However, Ribes and Polk (2014) asked scholars to be specific about what dimensions the infrastructure should be flexible around. The difficulty involved in tracing the evolution of an infrastructure against a particular dimension is often related to the indefinite nature of the objects of interest around which the KI are centred. Knorr-Cetina (1999) called such objects epistemic because they change as our knowledge of them evolves.

We build on the knowledge infrastructure literature (Østerlie et al. 2012; Ribes and Polk 2014) that called for better empirical and theoretical tools to investigate the evolution of knowledge infrastructures for tracking undefined or ontologically evolving objects of investigation, which brings the 'how' of knowledge production to the forefront.

2.2 Environmental risk

Environmental risk, especially in connection with the contested domain of oil and gas operations, is a vivid example of an epistemic object. A well-established view in sociology is that risk is 'constructed'. Risk is not a material or natural thing but emerges through a complex negotiation between what can be sensed, represented, and valued. Thus, risk becomes 'real' (i.e., an object) when enacted as part of a practice (Mol 2002, p. 44). It is framed as part of events that occur and plays that are staged.

Jasanoff (1999) demonstrated how risk is the result of cultural context: "Trying to assess risk is therefore a *social and political exercise*, even when the methods employed are the seemingly technical routines of quantitative risk assessment" (Jasanoff 1999, p. 150 emphasis added). Beck's 'Risk Society' is a relevant starting point to consider infrastructuring practices as a knowledge problem. It is not the outside natural world that is the cause of risk, Beck argues, but human knowledge of it. However, the results and means of knowledge (science and technology) are not only the problem but also "provide the means to recognize and present problems as problems at all, or just not to do so" (Beck 1992, p. 163), and to overcome those same threats. If we shift the problem from one of application to one of knowledge, the external element is removed and we have two consequences: the process of knowledge building is central and "contexts of origin and application push together" because consequences are "made *in the sciences themselves*" (Beck 1992, p. 170 emphasis in original).

We are not trying to enter into a complex sociological debate in this paper. We will limit ourselves to referring to Bruno Latour's commentary on Ulrich Beck's book (Latour 2003). Latour commented that Beck, as a sociologist, is interested in society as a whole, not in the local conditions that make the whole possible and visible in practice. Therefore, there is a local/global tension that emerges if we also investigate the latter.

Our aim is to explore further the emerging tensions specifically in relation to environmental risk in connection with oil and gas operations. For example, this subject has been a theme in marine policy and pollution journals (e.g., Elliott 2014; Gass and Murray Roberts 2006; Knol and Arbo 2014). Several studies have emphasised the networked and almost infrastructural nature of environmental risk assessment (Blanchard et al. 2014; Hauge et al. 2014; Knol 2013). There is a complex relationship between socio-political choices and their environmental consequences, e.g., the development of marine governance policies and types of accidents. Some authors have stressed the need to investigate the reasons for uncertainties associated with the side effects of routine operations rather than with major accidents, such as large oil spills (Blanchard et al. 2014). Some scholars have also investigated applications of the precautionary principle in marine ecosystem governance to reduce potential harms related to daily operations (Knol 2011). As Hauge et al. (2014) stated, there is also a connection between the less visible details of quantitative risk assessment procedures and how knowledge emerges; the former can restrict the debate on the issues and uncertainties that are considered relevant at the level of deciding the scope of risk assessment, the methodologies, and the presentation of results. The authors noted that the perception of environmental risk is influenced by risk assessment methodologies, i.e., "[a]ll these choices are value-laden because they have the potential to influence perceptions on what is at risk, how high the risk is, and what ought to be done with regard to the issue" (Hauge et al. 2014, p. 88).

In summary, we cannot fully understand environmental risk assessment without a stronger focus on its infrastructural nature – that is able to acknowledge the continuous interplay between the whole and the local – and the role played by the material elements in addition to the social and political ones. Risk assessment is indeed a socio-political exercise; however, it is also something more viz. both infrastructural and material.

3. CASE

3.1 The Norwegian continental shelf and the uncertainties of environmental monitoring

The waters off Norway are home to the world's largest population of a species of cold-water coral called *Lophelia pertusa* (Fosså et al. 2002). The corals are centres of complex marine ecosystems, where fish and other marine species seek shelter and food (Costello et al. 2005). The areas offshore of North Norway and the Lofoten Islands also host some of the world's largest stocks of fish, particularly cod and herring, which migrate there from the Barents Sea to spawn. Their eggs and larvae later drift back towards the Barents Sea by following the water currents (Hauge et al. 2014). In addition to substantial economic interest going back thousands of years, the coastline is scenic and attractive for both tourism and recreation.

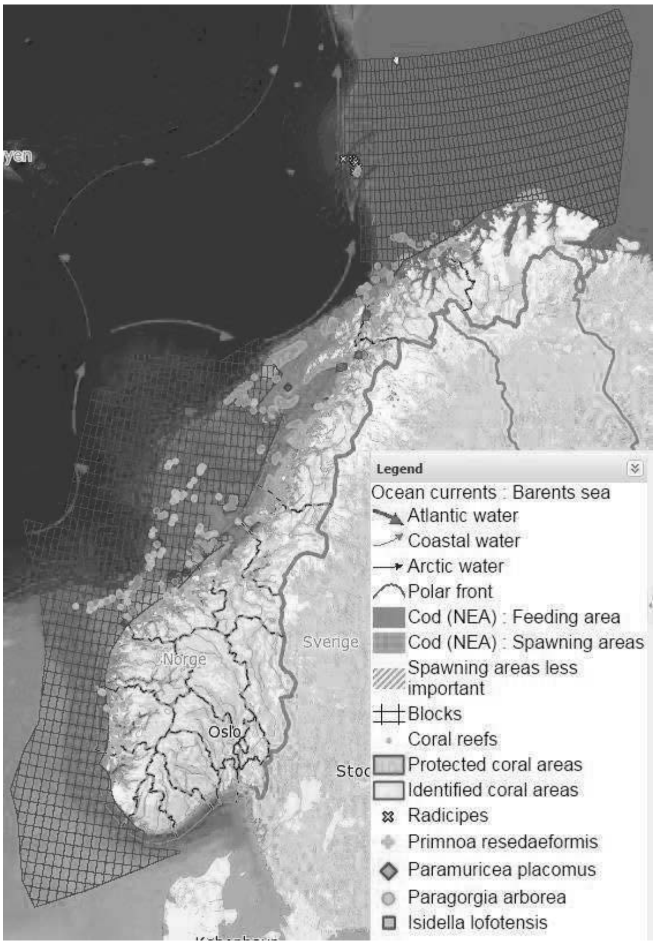


Figure 1. The Norwegian continental shelf, with operational blocks assigned by the Norwegian government (squares); areas of spawning cod (orange shapes); coral reefs (orange, red, and pink dots); and water currents (red arrows). Adapted from www.mareano.no.

Since the discovery of hydrocarbons in the North Sea in the late 1960s, there have been political, economic, and social controversies between fishery and environmental concerns on the one hand, and oil and gas operations on the other hand. Alongside this constant debate, the oil and gas sector in Norway has developed an intricate network of rigs, platforms, pipelines, vessels, and fibre-optic cables to explore, extract, and produce resources. Currently, 78 oil and natural gas fields are active in Norwegian waters (MPE 2014), corresponding to thousands of wells (figure 1). The socio-economic significance of the oil and gas sector represents approximately 25% of the GNP (SE 2014), the largest export, employs approximately 15% of the non-public workforce, and has accumulated one of the largest governmental investment funds in the world.

The constant hum of controversy surrounding oil and gas operations in Norway is regularly accentuated by particularly antagonistic issues. The present issue of whether to allow oil operations in Lofoten, which is the richest fishing ground in the country, is a vivid example (Blanchard et al. 2014; NME 2005). The pressure to open the areas is related, among other factors, to the estimate that approximately 24% of the world's and 30% of Norway's undiscovered oil and natural gas resources are hidden above the Polar Circle (Hasle et al. 2009). Norway is one of only five countries in the world directly facing the so-called High North. Those areas are characterised by harsh weather conditions and environmentally sensitive habitats. Moreover, there is little or sparse knowledge about the baseline behaviour of these habitats and on the possible effects of oil and gas activities in the vicinity. In making a provocative statement to emphasise that there is no real scientific background behind risk assessment calculations, the Norwegian Institute for Marine Research argued that "between 0 and 100 per cent of a cohort of fish spawn can be lost by an oil spill" (http://www.tu.no 24 April 2009). However, oil and gas companies have criticised scientists for being overly cautious, i.e., for exaggerating the precautionary considerations in the risk calculation process. Risk mitigation measures are generally taken by oil and gas companies operating on the Norwegian continental shelf in a reactive manner by following regulations that were set in advance by authorities and politicians (Hasle et al. 2009). However, these regulations are often indefinite and general (Hauge et al. 2014). The Norwegian Directorate for Nature management argued that the risk models developed for the areas offshore of North Norway do not account for local conditions, e.g., narrow fjords, local currents, tides, and wind (http://www.aftenposten.no 12 October 2011).

Partly because of a focus on safety, oil and gas operations have traditionally been fairly conservative and exhibit slow changes. Old habits and practices die slowly. Against this backdrop, ongoing efforts to create an environmental risk-monitoring infrastructure should be recognised as experimentation and innovation at the fringes. This experimentation creates space and opportunity to explore how environmental risk is to be rendered; however, it also poses challenges for appropriation or institutionalisation of tools, practices and formal procedures. Infrastructural inversion (Bowker 1994) exposes the inner mechanisms of knowledge production in infrastructures. Edwards (2010) went as far as stating that it is not only the researcher but also the actors themselves who perform an inversion, which can be seen as a form of articulation work (Kaltenbrunner 2014). In this way, inversion becomes a *generative* resource for infrastructuring, and it is appropriated by actors on the field to "reinterpret the status quo of infrastructure in light of potentialities, thus paving the way for embedding new tools in particular ways" (Kaltenbrunner 2014, p. 19).

3.2 The Venus observatory

NorthOil is a partly state-controlled oil and gas company that is the primary operator in Norway. Founded in the early 1970s, the company was historically organised around a geographically local operational site. Currently, NorthOil is promoting the development of cross-disciplinary and cross-geographical infrastructures, which are supported by the installation of collaborative work technologies (e.g., SAP and Microsoft SharePoint) and the installation of fibre-optic Internet connections that allow for faster communication between offshore sites and onshore control centres.

Given the strategic location of Norway relative to the High North, NorthOil decided to create baseline oceanographic parameters halfway between the more familiar Norwegian Sea and the unwelcoming High North. An ocean observatory was thus installed in the mid-2000s on the sea floor in the Venus area, approximately 20 km off the Lofoten Islands, directly above the Arctic Circle. The Venus project was conducted in collaboration with marine research institutes and technology vendors. The observatory consisted of a metallic semi-conic structure equipped with a few off-the-shelf sensors to detect basic environmental parameters, e.g., sound, pressure, temperature, turbidity, chlorophyll, and floating biomass. In addition, a camera and a camera flash were placed on a satellite crane to take pictures of a coral reef that was selected by project participants (see figure 2).

Figure 2. Graphic representation of the Venus subsea ocean observatory (source: http://lovedev.azurewebsites.net/).

The project was considered successful and strategically relevant; therefore it received funding in late 2011 from the Production and Development Department of NorthOil. In 2013, the observatory was connected to the shore with a fibre-optic cable. Environmental data began to be fed into a publicly accessible web portal in real time. An environmental advisor from NorthOil summarised their intention to operate and how they could use the data to demonstrate their ability to drill safely and increase the operational window as follows:

> "*We want to look at different types and possible technologies or methods to get this done. (…) Our argument is that if we can measure the biomass, we can maybe avoid having a general stop in drilling activities over a given period. If we can argue that we can measure when the biomass comes, either when fish come or go or when the spawning products return, we can stop drilling on time before the products return. Therefore, you can control the drilling and optimise your drilling [schedule].*"

NorthOil was interested in using real-time data to find a correlation between the time of the year and the marine biomass concentration (fish, eggs, and larvae). By analysing the trends over several years, a threshold value could be obtained to indicate the beginning and end of the spawning season. Therefore, the operational window could be set outside this interval.

4. RESEARCH METHOD

4.1 Data access, data collection, and data analysis

This paper is the result of a longitudinal ethnographic study conducted within NorthOil. Even in the traditionally open Scandinavian environment, access to an oil and gas organisation is not a straightforward issue for external researchers because of the political and economic sensitivity of national energy strategies and the recent budget cuts to R&D in most of the western world. The first author was granted a pass to NorthOil's R&D department through one member of our research team who also holds a full-time senior position in NorthOil and has a long-term history of collaboration with the second author.

Because gaining access to an oil and gas organisation is difficult, it must be treasured once obtained. Therefore, the first author spent as much time as possible at the field site, spanning an average of 2-3 days per week for two years beginning in April 2012. She was initially granted a desk at the entrance of the department where projects related to environmental monitoring were happening. However, sitting next to the entrance is equivalent to having a 'guest' label. Not all information is shared with guests. As the researcher began to take part in some meetings and follow a few informants to coffee breaks and lunch breaks, the employees became more accustomed to her presence. In November 2012, the head of the section, who initially granted her the badge, also allowed her to use a desk in an open-space office shared with key participants in NorthOil's real-time environmental monitoring programs. Along with this physical vicinity, access to information was greatly increased. It is recognised in the recent literature that corporations today often hire ethnographers, like anthropologists, to collect qualitative data on the functioning of daily work (Hepsø 2013). On the one hand, this habit makes the subjects in the field more comfortable with being observed. However, on the other hand, it does not guarantee an easier life for external personnel. To blend with our informants, the researcher regularly went to the office at approximately 8:30 and left after 16:00 like other employees on days dedicated to fieldwork. Together with the constantly visible NorthOil badge, this approach allowed the researcher to look like one of the individuals working within the department. In fact, she was mistaken for a full-time employee several times. Therefore, she was invited to most of the meetings, workshops, and teleconferences with external partners and technology vendors in addition to other NorthOil offices located elsewhere in the world. She also had facilitated access to people who could grant her access internal documentation (reports, presentations, and deliverables) and semi-structured interviews (33 in total). Interviews were initially conducted with NorthOil employees and later with employees of other companies that were collaborating with NorthOil, namely nine environmental advisors from a company active in risk assessment and quality certification and one project manager from a technology vendor company. We travelled a few times by plane to personally interview people located in other Norwegian cities. Observations have been constant (hundreds of pages of field notes) and fundamental for identifying informants and documents at the internal team sites. As a consequence, the second author could also participate in several events and in the interview collection process. Data collection occurred regularly until April 2014. Henceforth, the first author has only occasionally visited the NorthOil R&D department to conduct short follow-up discussions regarding the themes emerging from the data analysis process.

Data analysis proceeded in parallel with data collection and was aided by a discussion between the two authors and with the members of the research group. In line with an interpretive tradition stemming from the field of information systems (Klein and Myers 1999; Walsham 1995), we relied on several iterations to make sense of the empirical data. Initially guided by our research question, we were interested in finding snapshots of the practical mechanisms of the unfolding of the infrastructure for real-time monitoring. The iterative analysis has been constantly guided by our intention to shift our attention from the artefacts (web portals, sensors, and subsea observatories) to the infrastructures that sustain these artefacts across space and time (Edwards et al. 2013; Monteiro et al. 2013). In doing so, we operationalised Bowker's infrastructural inversion (1994), which is an approach that has influenced our data access, collection, and analysis strategies and has recently received much attention in the literature (Edwards 2010; Kaltenbrunner 2014; Mayernik et al. 2013). However, this approach tends to leave its dynamics underspecified, particularly when the investigation of a large-scale (and long-term) infrastructure is primarily in the hands of a single researcher for a limited number of years. Following the suggestions of Ribes (2014) and Beaulieu (2010), we identified key relevant actors in the field and aligned with them, assuming that they were also addressing our same research question. A relevant consequence of this strategy was that we were asked for feedback or for help with small tasks in the Venus project (e.g., commenting on a draft document) as our familiarity with those key actors improved.

5. FINDINGS: THREE INFRASTRUCTURING STRATEGIES

5.1 Sensoring – the devices used to detect environmental resources

Given the inherent uncertainties in quantifying the short-term usefulness of the Venus project for NorthOil, the sensors installed on the observatory were rather inexpensive, off-the-shelf devices that are also typically used by fishermen. The project participants had to employ what was already available. In particular, two ADCPs (acoustic Doppler current profiler) were installed. The ADCP is an active acoustic device that has been used since the late 1980s for current profiling. In principle, it sends an acoustic signal at fixed intervals (shorter than 1 s) and measures the strength of the signal returned when a target is hit in the water column (the so-called backscattering value) within its audible range, which depends on predefined settings. The adoption of ADCPs by the Venus project relied on two elements of novelty.

The first innovation dealt with the interpretation of the measurements. The project members soon realised that the backscattering value could be intrinsically useful even outside the current profiling purposes. This instrument could be used to obtain the size of the target, where a target could be a fish, a fish egg, a larva, or even zooplankton in the water column (e.g., figure 3). Other types of acoustic devices that have been developed to obtain these measurements and were available to NorthOil could have been used; however, according to environmental experts, the ADCP is capable of detecting resources as small as zooplankton, which are almost impossible to locate with other devices using longer wavelengths. However, this ability is only a wish for the future. Not only the detection of zooplankton but also of eggs and larvae was very low in the Venus observatory (refer to figure 4 for a schematic example). As a consequence, computer models of the dispersion of eggs and larvae drifting along with the water currents were integrated to obtain the missing data.

> "*One example is that we want to monitor larvae and egg drifting through the bottom masses; but (…) [w]e know [that the Venus ocean observatory] is not able to monitor that. So what do we do then? (…) The equipment will be better in a few years perhaps, 'cause we know that there are organisms that are vulnerable for oil pollution, much more vulnerable than adult fish, which can swim away from the oil but [larvae can't]*"

Figure 3. Fish swimming over a coral reef (source: www.mareano.no).

A second innovation introduced by the Venus project is related to the positioning of the ADCPs. These instruments are typically installed on boats and are pointed downwards when used by fishermen.

Placing the acoustic devices on the sea floor means that the new measurements are obtained looking up rather than from the top down (figure 4). This approach had an unpredicted consequence. The way in which upward-looking data should be interpreted is not obvious. The most visible fish for an acoustic device are those that have a swim bladder, i.e., an internal organ located in the dorsal portion of the fish that not only allows it to control its buoyancy but also to emit and receive sounds, reflecting a stronger signal (Simmonds and MacLennan 2005). However, time series collected by other research institutions have always been taken top down. As a consequence, NorthOil data are not comparable with historical datasets and no expertise is currently available to interpret these data. Here is an excerpt from an interview with an environmental advisor from a partner company involved in NorthOil's project:

> *Advisor: "[T]he [ocean observatory] is on the bottom so it can't see [larvae and eggs]. So if you had a sensor or [ADCP] at the top, that would solve the problem probably."*
> *Interviewer: "But weren't [ADCPs] originally used from ships actually?"*
> *A: "Yes and that's also another problem about the [Venus project] that is that the fish experts they don't have any experience about having the sensors from bottom, that goes from bottom. So they don't know the echo actually from the under part of the fish. As this expert told us today they need to set up a project on that."*
> *I: "So there is no experience whatsoever of using [ADCPs] from bottom to top?"*
> *A: "No."*

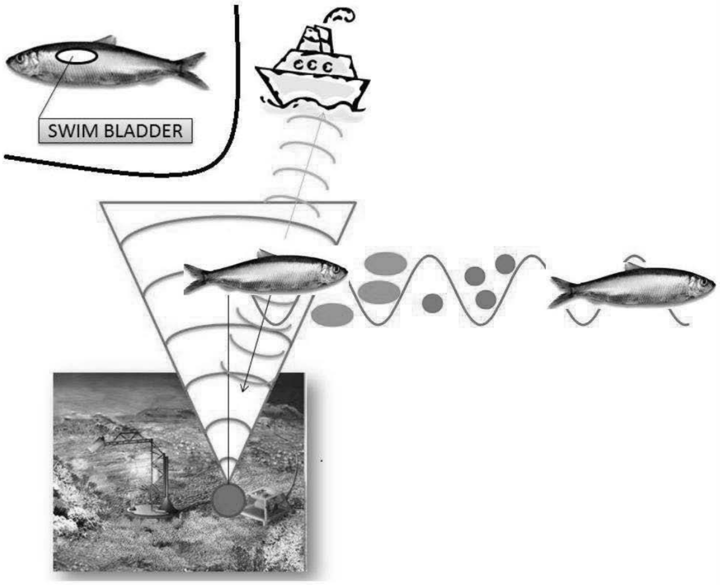


Figure 4. Approximate position of the swim bladder and exaggerated schematic representation of two directions used to spot fish (vertical, from the sea floor as in Venus or from a boat). The sound waves are often unable to spot resources smaller than their wavelength (horizontal sinusoid). Figure adapted from http://lovedev.azurewebsites.net/.

5.2 Validating

NorthOil's goal was to automate the process of real-time environmental risk prediction. However, even when data are available at sufficient granularity, they must be validated. In other words, because the sensors are placed at unmanned subsea locations, data must be assessed for trustworthiness.

A few NorthOil employees close to the Venus project decided to investigate the routines adopted by the company to handle real-time data during daily operations, e.g., when a new well is drilled. The idea was to borrow insights and adapt those routines to the environmental domain.

As is the case for many oil and gas companies, NorthOil has a dedicated support centre (called here Online Support Centre, or OSC) whose scope is to determine the technical quality of the data gathered by the service companies in charge of the drilling operations on behalf of NorthOil. The drilling of a new well is a delicate phase that must be carefully monitored to prevent accidents that can range from a stuck drill pipe that halts operations for a few days and causes the loss of huge amounts of money to more serious consequences to the surrounding environment. However, knowing if things are going right or wrong is a challenging task when there is a lack of references against which to decide whether a given measurement respects the safety intervals. As one OSC employee stated, some errors can go completely unnoticed. Typical errors can occur in the sensor calibration:

> "*It could be that the data are shifted for some reason. Let's say that the whole data set as coming in is 5 meters too deep or 5 meters to shallow. We wouldn't be able to notice that (…) and that could be due to a calibration error to the sensor. We wouldn't be able to capture that.*"

Sometimes, the measurements from different service companies are not synchronised:

> "*We actually see them sometimes when we have two different service companies on the rig providing us with the same data. Then, we see them when we plot them on top of each other. Then we see that (…) there is not only a difference with regard to value but also a time reference. (…) Basically because the machines from various service companies offshore are not synch[ronised].*"

The OSC relies on both situated bottom-up workarounds and standardised approaches to overcome these tricky issues.

Situated quality assurance. The bottom-up method relies on the vicinity to the measuring points and the experience of the offshore personnel, because they have developed a grounded knowledge of the site and the well. The same employee continued as follows:

> "*[I]t is up to the data owners out in the asset, because they know the formation, know they are supposed to hit this and this layer and so forth, they are fully responsible for*

> *the overall and the petro-physical quality of the data. And that requires a human to look at the screens and basically perform that type of checking.*"

Therefore, data validation cannot occur without local experience of the site. The same is true when an error is reported in the incoming dataset. Another OSC member echoed his colleague:

> *"[W]hen you have typically [Driller A] doing an MWD [measurement while drilling] and you have [Driller B] doing surface in the same rig, they are not doing the same depth references so they are both wrong or both right. (...) But actually to really fix this problem, then you have to really get closer to the sensors, to the system, and you have to really fix it offshore for every rig that is where you actually are solving it. And you need to monitor it, and follow it up. If you really would like to solve this problem, then you need to have a project, focused on one rig and make it right for that rig."*

The bonus/penalty contract. However, the OSC does not solely rely on the ability of offshore personnel to spot errors. Instead, the centre has developed a complex system of penalty and bonus contracts to either penalise or award service companies based on their capacity to provide trustworthy datasets. This system is currently so successful that it has also been applied to NorthOil's operations outside Norway. It is also relatively flexible because penalties or bonuses are directly proportional to the money a service company acquires for providing the datasets in each drilled section. More money is involved for well sections that are closer to the oil reservoir. This approach is standardised because the OSC applies it to all of its service companies. It is also a top-down approach that stems directly from the contract, regardless of the details of the subsurface sensors. As a result, the approach directly links money to the technical quality of data, triggering the development of better measurements from the service companies, indirectly becoming a metric for measuring the output datasets delivered:

> "*Because immediately when you see that, ok, you have a problem, and you penalise it, then they get initiative to improve their own system, and their own routine (...) [T]he bonus penalty is linked to the drilling service contract. And all this, the money typically a service company gets paid for drilling a 36-inch section is not a lot, because based on the tools they have in the hole, when we get into the reservoir section and the low well… then it's much more money involved in each one. So when you get a 5% bonus or 10% penalty for an 8,5-inch section it's completely different than getting it from a 36inch section (...) and we are the only oil company in the world capable of doing that. Because other oil companies are missing this basic metrics for actually measuring delivery, which data to expect.*"

5.3 Abstracting

The coral risk matrix. Even if the collected raw data are technically sound, it is often difficult to predict the risk associated with oil and gas operations using such data. Therefore, general procedures and abstractions are necessary. At the intersection between the oil and gas business and the environmental domain, one of the most famous cases of risk representations is the coral risk assessment, i.e., a method that was developed by a third-party environmental service company to predict the risk to corals, which are very dense in Norwegian waters. One of the experts who invented the methodology summarised its functions as follows:

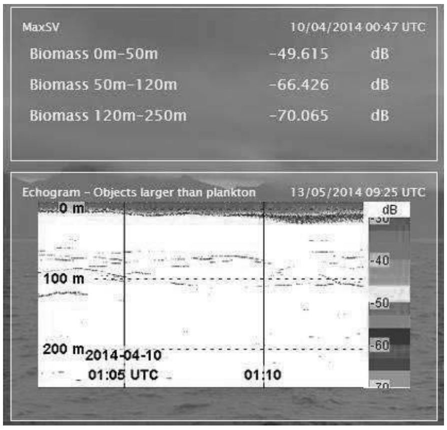
> "*[A]nd then we come into this coral risk assessment part (…) so we can express some kind of a risk to the operation (…). [W]e combined a probability based on the current measurements and we have established a consequence matrix where we give the different habitats a value. We implemented dispersion modelling into this, and when we combine it to this resource map of course we get a risk of conflict between discharges and the resources*."

Because corals are static resources, they are traditionally placed onto a 2D bathymetric map by surveyors. The map is subsequently overlapped with a prediction of the particle plume that is generated during a drilling operation. As a result, each coral structure is mapped onto a risk matrix (figure 5), which consists of the adaptation of a general-purpose risk visualisation tool to represent a coral as a risk object.

> "*Corals in Norway are [categorised into] 4 classes; therefore, you are putting some value on your resource. That is important to us. If you want to do risky, you need to value resources, and corals are valued into the four classes (…) based on… area is one thing, height, also the size.*"

The risk matrix displays the probability for a coral to be hit by the discharge plume (likely, large, moderate, or small) by considering the consequences that the discharged particles may have on the specific coral (i.e., if the coral is healthy, the consequences would be severe; if it is dead, the consequences would be minor or none).

In general, corals that are closer to the source of the discharges or located in the same direction of the water current with respect to the discharge point deserve more attention. Experience-based assessments provide guidance for safe distances to environmental experts (i.e., 500 m rather than 50 m). Boundary values are generally set for each specific case in collaboration between third-party experts and the Norwegian authorities. Therefore, the risk matrix becomes part of a metadata set, which is a universal list of attributes describing a coral structure that is used to archive data and to compare data from different surveys. Because the coral risk assessment methodology has been adopted by the Norwegian Oil and Gas Association, the risk matrix is one of the tools that are currently used by operators to locate safe drilling locations. Therefore, it has become an infrastructural element for oil and gas operations in Norwegian waters.



MaxSV 10/04/2014 00:47 UTC

Biomass 0m-50m	-49.615	dB
Biomass 50m-120m	-66.426	dB
Biomass 120m-250m	-70.065	dB

		Consequence			
		Minor	Low	Considerable	Severe
Probability	Likely				
	Large				
	Moderate				
	Small				CR-01

Figure 5. Top: Environmental value above a chromatogram (source: http://lovedev.azurewebsites.net/). Bottom: Coral risk matrix (a reproduction by the authors).

The environmental value. It is not easy to assess the risk associated with moving marine resources. A typical model for displaying the ADCP measurements is the chromatogram, in which measurements are plotted over time and coloured in different ways based on the concentration of marine biomass at a given depth (see figure 5). A chromatogram for the area surrounding the Venus station was displayed on the Venus web portal.

In late 2013, a few members of the Venus project travelled to a small town in the Lofoten Islands to present the Venus web portal to a local community of fishermen. Positive feedback was received. A local newspaper wrote enthusiastically that the portal was becoming “More popular than Disney Channel” (figure 6). However, the fishermen also noted that the chromatogram is too densely populated with data and too difficult to read for their purposes. NorthOil had to maintain the interest of the fishermen because of their grounded knowledge of the area. Again, bottom-up feedback was fundamental.

In addition, the chromatogram’s granularity was also deemed excessive by environmental experts because users of the analysed environmental trends want to receive results on a monthly basis; their databases are not ready for such detailed datasets.

As a consequence, the project directors had to find an alternative solution. They finally decided to synthesise the water column into a discrete set of values. NorthOil and its research partners formulated the idea of adopting a biomass indicator that is called the 'environmental value', inheriting an earlier term from the Norwegian Directorate for the Environment to summarise the biomass concentration in larger chunks of the water column (figure 5). The environmental value is obtained by collapsing a subset of the original sections scanned by the echo sounders into one; measurements are provided at hourly intervals instead of every few seconds. This strategy enhanced not only the visualisation but also the storing of data streams, generating much fewer data entries every hour. As presented during a 6-hour project meeting with representatives from NorthOil and the partner companies, the environmental value has been defined by two participants as a "*newly cooked term*" meant "*to express environmental happiness!*"

As described in the previous paragraph, an approach based on identifying environmental resources and tagging them with a risk value is not new to the oil and gas sector. As one environmental advisor stated, the environmental value is in fact the evolution of the risk matrix applied to moving marine biomass:

> "*[W]e want to do [the coral risk assessment] more generic, meaning that other environmental resources… it can be used for other environmental resources as well. So far it has only been used for corals, but obviously you can have first all what do you call it… sessile species, the animals and plants living on the sea floor which are there stuck. But you can also think of using the same method on the pelagic species like fish and things that swim around and move.*"

The dynamic nature of fish and marine biomass requires the environmental value to be a relative measure, i.e., it means different things at different moments and in different locations.

Two fish in usually deserted areas represent a high concentration, whereas two fish in an otherwise densely populated location represent a low concentration. Therefore, categories must be calibrated with historical data that are currently not available to NorthOil. Having enough data to bootstrap this relative categorisation is vital for NorthOil to set up an infrastructure for environmental risk management.

FORSIDEN/NYHETER/BØ/ - MER POPULÆRT ENN DISNEY CHANNEL

BILDE 1/4

Ekkolodd på mobilen: [redacted] utviklingsavdeling har hentet opp ekkoloddet fra Holla på mobilen. Kollega [redacted] til høyre.

1 2 3 4

- Mer populært enn Disney Channel

Nå kan du se reality-tv fra havbunnen utenfor Bø. Tirsdag åpnet havobservatoriumet til [redacted] og Havforskningsinstituttet, som også kan bli nyttig for lokale fiskere.

BØ Dag Erlandsen, Kyst og Fjord Publisert: 12.12.2013 09:30 Sist oppdatert: 12.12.2013 09:32

Figure 6. Newspaper reporting on the workshop between NorthOil and the fishermen. The article title is "More popular than Disney Channel. Now you can see reality TV from the sea floor outside Bø. On Thursday, the ocean observatory of [NorthOil] and the Marine Research Institute was opened. It can also be useful for local fishermen" (source: http://www.vol.no 12 December 2013).

6. DISCUSSION: SEEKING ENVIRONMENTAL HAPPINESS?

6.1 Infrastructuring the global in the local

The purpose of embarking on environmental risk monitoring is to create a 'global' account in the sense that you assess not only the specific measurements that are actually collected but also the risk of extended regions/areas or habitats (cf. Power 1999). As Porter (1996) described, this assumes quantification to allow local measurements to travel and involves grappling with certain spatial tensions we discuss.

First, there is a spatial connection between the working method and the perspective we have on certain phenomena. Infrastructural inversion is often about reversing this spatial order. Almklov and Hepsø (2011) described the mismatching interpretations of petroleum reservoirs by geologists and geophysicists, each of whom is accustomed to examining geological sedimentation layers in opposite directions, one from the bottom and the other from the top. In an analogous way, although the drilling process necessarily occurs from the top of the well, the OSC must make sense of the online data stream from the bottom. The same applies to the ADCPs deployed in Venus. Having originally been used on floating vessels, they are now turned upside down and made stationary to reside on the sea bed. The data remain the same; however, the altered spatial perspective (from the bottom and not the top) renders them different at the same time. Reversing these spatial orders also emphasises the material dynamics involved in measurements. ADCP acoustic signals collected from the bottom exhibit a different reflection when they encounter a fish swim bladder.

Second, there is continuous interplay between how data become accessible globally or beyond their context (either to onshore sites or to the general public) and knowledge of such data (acquired at the local level). This interplay is true for all vignettes presented in the previous section; the Venus project participants had to learn how the ADCP devices function with respect to the types of fish that populate the Venus region and that have a swim bladder. The OSC standard procedures that are based on bonus/penalty contracts must be extensively complemented by the experiences of offshore service companies related to subsea formations. The coral risk matrix, at a first sight, represents an outstanding exemplar of the creation of a vacuum or a void of context. Such a simplified representation is also useful to compare different environmental surveys taken in an area in different moments. However, upon scrutiny, it is not a vacuum. It embeds locally acquired expertise to assess what is a healthy coral reef and the experience needed to define a safe distance from a drilling location. More specifically, the process of building and sharing new knowledge critically depends on the experience of a local context (Zimmerman 2008). Therefore, the generative capabilities of infrastructuring practices are at the interface between the public or standardised (the global) and the very local. This process resonates with Latour's circulating reference (1999). As the world is reduced into inscriptions through measurements and simplifications ("*we give the different habitats a value*", see paragraph 5.3), local knowledge can become public and subsequently amplified ("*we can express some kind of risk to the operation*"). Global knowledge is made possible and visible locally (Latour 2003). This process is never-ending because NorthOil's attempt to (vertically) integrate a real-time environmental risk assessment chain opens new spaces for local practices. For example, there are efforts to relate the Venus data with an international network of related ocean observatories, e.g., SAM-X (www.epim.no/sam-x) for integrating marine data collected by fishery and oil and gas industries and the US National Oceanic and Atmospheric Administration (http://www.noaa.gov). This integration will create an open data platform for analysis. The environmental value is made 'global' but remains grounded in the historical data gathered from the local site. The more the Venus project relies on a global value, the more local knowledge of the Venus area is emphasised to improve the value. Local knowledge constantly affects 'global' values.

6.2 Infrastructuring a baseline: temporal tensions

NorthOil's efforts to use environmental monitoring to facilitate risk assessments are ostensibly about creating a KI for *real-time* data. However, there are a variety of competing time scales that are all imbricated with distinct materiality. We discuss the resulting tensions that stem from the incommensurability of temporal frames.

The time scale for offshore drilling engineers is seconds and minutes when responding to sensor-based pressure, torque, temperature and directional measurements. NorthOil itself seeks an operational window (i.e., a seasonal window determined by weather and other conditions) that is as wide as possible while remaining constrained by the formal decision gates that every newly deployed technology must go through in an oil and gas organisation. Months may be required for such decision gates to be reached. Governmental authorities grant oil operators the permission to drill after a period of months or even years. However, environmental risk prediction is based on natural time scales, with environmental advisors acting as its spokespersons; trends and effects may only become visible over years, decades, or centuries. For example, cold-water corals have been present in the Norwegian territory for more than 9000 years. The pollution of fish spawning products becomes visible only during the next generation, when cod larvae could die and fail to become adults after 3-4 years. Fish generations are also the concern of fishermen; they want knowledge of the present population as well as to make sure that there will be fish to catch during the following seasons. When asked about the dichotomy generated by the tension between a real-time approach to risk assessment and the long-term changes in nature, one NorthOil environmental chemist wondered if it makes sense to frame the environment in human-constructed patterns;

> *Interviewer: "[H]ow can you be proactive in assessing the environmental risk if you need a long time to monitor possible damage?"*
> *Environmental chemist: "That's a potential paradox of course but I guess that the easy, the obvious answer is that yes, you need to start to monitor early. It's too late if you have already done the drilling (…) when you start doing what you could define as a baseline, 'cause then it's not really a baseline. But then another existential question: is there such a thing called ecological baseline? Is that possible? Because no environment is constantly… constant over the whole time."*

Nonetheless, different conceptions of time must be frozen into different enactments of risk that make sense to the different stakeholders that are involved. The starting point is the risk matrix. It is a well-established infrastructural element in risk assessment with operational contexts that meld oil and gas with environmental domains. It represents a trade-off between what constitutes risk for the coral reefs (the damage might become visible over the course of several decades) and what constitutes risk for operations (being stopped, which is visible in only a few seconds). In extending the matrix, the environmental value was developed by adding one step to not only create real-time monitoring machinery but also to make it dynamic. Because no operations are currently permitted in the Venus region, the environmental value constitutes an indirect measure of risk and computes in a few seconds the *relative* amount of marine fauna that could potentially be affected. What used to be an offline, disconnected, and slow practice in which risk is often assessed in an ex-post manner, suddenly becomes fast, interconnected, and closely visible. This happens by balancing the years over which the environmental trends become clear and the seconds used by technology to measure them. Similarly, the bonus/penalty contract used by the OSC enacts risk as an economic risk for the service company. If we unpack the contract, it is the compromise between the months and years required by formal governance and the seconds with which drilling engineers operate.

This new real-time/long-term scenario opens the door to new ways of assessing the risk associated with present or future oil and gas activities. As a consequence, it dramatically shuffles and ultimately reduces the temporal gap between human operations and their possible consequences. In analysing how risk emerges as a phenomenon through the building of infrastructure, we should be specific about the agency of the material elements because, if the feedback loop between an action and its consequences is shortened, the performative (or generative) role of the combined materiality of nature and technology gives birth to new and unprecedented results.

Finally, shrinking the temporal loop between operations and environmental risk is also an issue of economics and politics that touches a business-sensitive nerve. It is not obvious if oil and gas companies are interested in raising the attention of authorities to the possibilities of new technologies and methodologies that they could be required to pay for and install. As one environmental advisor from a partner company commented when discussing the possibility of turning the coral risk assessment approach into a real-time method:

> "*[W]e've been talking to some companies about this [project] and some companies, they do not want to touch this kind of concept because they fear that, once they do, the government, the regulatory bodies will adapt it and take it as a requirement. So that working and putting… kind of bringing into new technologies and new ways of working like this might put new constraints to the operators. So that is very interesting actually. [NorthOil] is doing the opposite, thinking a little bit differently*."

6.3 Social infrastructuring and trust

The last facet of infrastructuring that we analyse here is associated with the application of trust building techniques by NorthOil. Following Schick and Winthereik (2013, p. 82), STS must also investigate how infrastructures are “constructed as a public problem in specific imaginative spaces of opportunity and closure”. We have seen some snapshots of the differences between two computer models, i.e., the chromatogram and the environmental value, and how they are related to the careful work of *social* infrastructuring by NorthOil around a specific problem, namely subsea environmental risk, for which no closure has been reached in public debates. The work of infrastructuring at the social level is as important as that at the technical level – if we want to draw upon Bowker’s idea (1994) of the importance of building an onshore social infrastructure that mirrors the subsurface (or subsea) infrastructure.

This aspect shows how the relationship between data and perception is inextricably connected to trust. In Yearly’s words, “Observations depend for their convincingness on a context of mutual trust” (Yearly 2009, p. 158), which is ultimately because, to quote one OSC employee, "*of course if you don't trust the data, you don't use the data, and some shit happens*". Conveying the message that the Venus web portal used to display real-time environmental data is better than the Disney Channel dampens the tensions generated by everything related to oil and gas. This message resonates with the definition of the environmental value as a “*measure of environmental happiness*”.

Several strategies, or social technologies (Shapin and Schaffer 1985; Yearly 2009), are embraced by NorthOil. First, in the context of the more traditional drilling operations, measurements are often conducted by one or more service companies (see section 5.2). Nonetheless, having third parties perform the work means that, as Zimmerman (2008, p. 648) remarked, trust alone is insufficient to transfer knowledge across distance; moreover, “it is the ability to comprehend data collected by others that is the key to their use”. This incomprehension occurs when the OSC lacks a reference to service company measurements, and “*they are not doing the same depth references so they are both wrong or both right.*” Second, the measurements collected for the Venus project are obtained in a non-operational area where no direct oil and gas interests can be claimed. Third, the Venus real-time data are published on a publicly accessible web portal. These two latter strategies assist in enforcing the genuine impression of the Venus project and hiding its business-related aspect.

7 CONCLUSIONS: THE POLITICS OF RISK

The politically charged character of ‘facts’, technologies, and numbers is well rehearsed in STS. In the case examined herein, environmental concerns that are related to oil operations represent a particularly vivid example. What can we make of the way in which the politics of risk unfolds?

First, the a priori antagonistic relationship between fishing/environment and oil operations has not and most likely will not result in a consensus. Instead of a stand-off awaiting consensus, we have a situation closer to what Barry (2013, p. 7) presents, where "[in] the presence of antagonism (…) decisions often have to be arrived at not by attaining a consensus, but in the face of persistent disagreement".

Second, there are not only profound uncertainties about environmental knowledge as we have described. There are also uncertainties or ambiguities regarding what constitutes oil 'operations'. The Lofoten area is presently off limits to oil operations (qua drilling and production); yet, the area is subject to seismic 'surveys'. Seismic surveys are conducted by shooting bursts of seismic sound waves from long cables trailing vessels directed at the seabed and reading off the echoes. As some environmentalists have noted, this is likely to be harmful to whales and other sea life, although nobody knows to what extent. One marine biologist, who was quoted in a local newspaper (Klassekampen 19 July 2014), uses hydrophones to listen to the singing of sperm whales, which are the largest of the toothed whales, in the vicinity of Lofoten. She then detects the seismics from the ongoing "surveying". Through the hydrophones, the seismics sound like "thunder" or "explosions" and cause the whales' singing to subside. She reports that the explosions go on and on; however, she exclaimed, "*They tell us Lofoten is sheltered from oil operations. That is political bollocks. This ocean is severely affected. It is only that we cannot hear it [without sensors such as hydrophones]*."

Third, NorthOil's proactive strategy for online, publicly open KI on environmental monitoring is rare among oil operators. Traditionally, the operators have taken more of a back seat role (Behrends et al. 2013). This strategy is also debated within NorthOil. Some argue that openness is a prerequisite for achieving credibility, including cases of legal liabilities, with governmental agencies. As one environmental chemist stated, *"Environmental data [are] of extremely little value if [they are] not being published and [we] are not being open with [them]."* Meanwhile, the current strategy of openness might be closed later when/if the economic value of environmental data increases: *"There is not so much profit involved in [environmental data]. For the moment!*" (senior researcher, NorthOil).

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Paper VII

Paper 7

Environmental Sustainability: Implications for Green IS

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ENVIRONMENTAL SUSTAINABILITY IN OIL AND GAS OPERATIONS: IMPLICATIONS FOR GREEN IS

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Abstract. Green Information Systems (Green IS) explores the opportunities for information and communication technology (ICT) to ensure environmentally sustainable business processes. To date, however, the field has been dominated by studies on the impact of singular tools and artifacts, thus lacking attention toward the distributed, interactive, and highly interconnected nature of information technologies. This shortcoming is mirrored on the theoretical level by the inability to engage with the most recent conceptualizations of the interplay between technology, work, and knowledge in organizational realities.

We propose a revitalization of Green IS. First, we present a longitudinal case study from the environmentally contested oil and gas industry. We describe and analyze a large-scale effort by an international oil operator to establish real-time subsea environmental monitoring during well operations. Second, drawing on insights from sociomateriality, we demonstrate the material (technological) circumstances of how environmental monitoring is performed. 'Facts' about the environment are inheritably tied to the technological means of their production. Third, we demonstrate how an infrastructure-based lens allows capitalizing on the properties of interactivity, distribution, and integration of ICT systems to enhance environmental sustainability.

Keywords: Green IS, Environmental sustainability, Sociomateriality, Information infrastructures, Oil and gas

INTRODUCTION

The nascent but growing research stream on Green Information Systems (IS) targets the transformative opportunities of information and communication technology (ICT) to address the challenges of environmental sustainability. It is driven by a growing sense of urgency. As the introduction to the recent MISQ Special Issue on environmental sustainability passionately pleads, "[t]he challenge of climate change poses enormous and widespread risk to people, societies, and the natural environment. The threat is real. The threat is colossal. And the threat is ever increasing. This is the challenge of great urgency." (Malhotra et al. 2013, p. 1265)

Despite the scale of the challenges targeted, the research stream on Green IS has been dominated by "smaller" efforts, including energy-efficient technology (e.g., Corbett 2013a; Hilpert et al. 2013), employee persuasion systems (e.g., Chen et al. 2009; Molla and Abareshi 2012), energy consumption tools (e.g., Marett et al. 2013), and sustainability reporting (Bengtsson and Ågerfalk 2011). A large part of the research on Green IS has involved developing models, formulating strategies or conceptual frameworks without empirical data (e.g., Bose and Luo 2011; Dao et al. 2011), and conducting surveys (e.g., Chen et al. 2009; Ryoo and Koo 2013) or experiments (Loock et al. 2013). We review the Green IS literature and identify two shortcomings: first, the absence of recent conceptualizations of technology in the IS and organization studies literature (e.g., as proposed within sociomateriality); second, a lack of attention to the distributed, interconnected, and interactional nature of IS.

We draw on an in-depth, longitudinal case study (2012 – 2014) of an oil and gas operator's ongoing efforts to establish a novel capacity for real-time, sensor-based monitoring of the subsea environment. The relevance and importance to Green IS is that environmental monitoring is at the center of the heated debate regarding which areas to ban from oil and gas operations for environmental reasons. Nowhere do the tensions and conflicts run higher between energy interests and environmental concerns than in the High North: an estimated 25% of the remaining unexplored oil is in or near the Arctic (Bird et al. 2008). The same areas are simultaneously particularly vulnerable to pollution and host the richest fishing grounds on the planet.

We make three contributions in this study. First, our case study responds to the paucity of longitudinal accounts of how efforts to enhance environmental sustainability unfold over time within a contested sector, such as the oil and gas industry.

Second, drawing on a sociomateriality perspective of IS (Cecez-Kecmanovic et al. 2014; Orlikowski and Scott 2008), we discuss how the materiality of environmental monitoring (sensors, instruments, measuring devices, networks and analysis algorithms) constructs the way the environment is re-presented in non-neutral ways.

Third, drawing on an infrastructure perspective in IS (Hanseth and Lyytinen 2010; Monteiro et al. 2013; Williams and Pollock 2012), we discuss how environmental monitoring emerges out of an extensive and open-ended set ("infrastructure") of systems, tools and work routines rather than any singular artifact. Given the politicized nature of oil and gas operations in the Arctic, we reflect on the implications when 'facts' about the environment are necessarily constructed by the specific material configurations of the environmental monitoring infrastructure.

1. INFORMATION SYSTEMS FOR ENVIRONMENTALLY SUSTAINABLE PROCESSES

The field of IS for environmental sustainability was born as an attempt to draw the attention and contribution of IS research to the problem of environmental sustainability (Malhotra et al. 2013). The field has recently evolved into two research streams, Green information technology (Green IT) and Green IS (Loeser 2013; Watson et al. 2008). Whereas the former is "mainly focused on energy efficiency and equipment utilization," the latter refers to "the design and implementation of information systems that contribute to sustainable business processes." In sum, "Green IS has a greater potential than green IT because it *tackles a much larger problem.* It can *make entire systems* more sustainable compared to reducing the energy required to operate information technologies." (Watson et al. 2008, p. 3 emphasis added)

In the last few years, a growing number of papers have been published in key IS outlets to address IS for environmental sustainability. The theme has also gained broader visibility due to the recent MISQ special issue on "IS & Environmental Sustainability" (Malhotra et al. 2013) and the constant presence of dedicated tracks in most recent editions of the top IS conferences (European Conference on IS 2014 track on "Sustainably digital," International Conference on IS 2013 on "Green IS and Sustainability," as well as AMCIS 2012, 2013, and 2014 on "Green IS").

2.1 Results from the Literature Review

In the introduction to the MISQ Special Issue on Green IS in 2013, the editors review the literature from 2008 to 2013 and note that the majority of the contributions consist of literature reviews and conceptual frameworks as well as of an analysis of empirical case studies (Malhotra et al. 2013).

We conducted a systematic literature review of Green IS in 2008-2014 as described in Appendix. We identified 21 articles published in the basket of journals of the Association of IS and in the principal IS conferences. We classified the articles according to the unit of analysis ("*What is being investigated*?"), the research method adopted ("*How was the study conducted?*"), and the type of contribution provided (e.g., a conceptual framework rather than an empirical analysis) ("*Contribution?*"). The key observations that emerged during our review are identified below.

-- TABLE 1 about here --

Research methods ("How"): The most striking observation is the lack of empirical studies in the field of study on Green IS. A review conducted in 2011 on a broad set of IS outlets remarked on a paucity of empirical research in the area (Jenkin et al. 2011). This still prevails. Only 10 out of 21 papers are based on case studies, including the effects of an IT-supported reporting and analysis system for sustainability (Bengtsson and Ågerfalk 2011), Carbon Management Systems (Corbett 2013a), commercial long-haul truck driving (Marett et al. 2013), and manufacturing firms (Ryoo and Koo 2013).

Different research approaches are adopted in the empirical studies that we retrieved. The theme of Green IS can be addressed through different philosophical perspectives in IS: positivist, interpretive, critical, and design science (Melville 2010). The methodologies of data collection vary accordingly. Only a few contributions draw on case studies (e.g., Bengtsson and Ågerfalk 2011; Corbett 2013a), whereas surveys are better represented (e.g., Chen et al. 2009; Corbett 2013b; Marett et al. 2013; Molla and Abareshi 2012; Ryoo and Koo 2013). For example, Corbett (2013b) uses the data collected from hundreds of US electricity utilities. In a different study, a web portal traffic is analyzed through a field experiment (Loock et al. 2013).

Five contributions are based on literature reviews (e.g., Chasin 2014; Chowdhury 2012). These studies generate theoretical frameworks, e.g., to provide the groundwork for a discourse on the meaning of the concept of sustainability and to outline recommendations for future research (Chasin 2014). Chowdhury (2012) uses a literature analysis to propose the cloud computing model as a solution for Green IS. Four articles contain propositions for a research agenda for Green IS (e.g., Melville 2010; Watson et al. 2010).

Unit of analysis ("What"): We identified six studies that focus on the relationship between artifacts and users to afford environmentally sustainable behaviors, an approach that complies with the definition of Green IT rather than Green IS. Examples include smart meters (Corbett 2013b; Loock et al. 2013), carbon-management systems (Corbett 2013a), and greenhouse-gas tools (Hilpert et al. 2013).

Melville (2010) insists on the critical role that IS can play in shaping beliefs about the environment. Seven out of 21 studies accordingly investigate the driving factors that persuade users to adopt environmentally sustainable technologies. This involves analyzing what persuades the employees of a company "to perform ecologically responsible behaviors" (Corbett 2013a, p. 339) or into "establishing environmentally sustainable work practices" (Seidel et al. 2013, p. 1276). Jenkin et al. (2011) find a positive correlation between the environmental orientation of organizations and that of their employees. However, economic benefits are also found to motivate employees to install, e.g., bypass systems on trucks (Marett et al. 2013). Others identify cost cutting and energy conservation as drivers for organizations to adopt green technologies (Molla and Abareshi 2012).

Finally, most studies treat the role of the environment merely as a background and thus external as, e.g., "'strategic' IS for environmental sustainability allow companies to proactively transform value chain activities to benefit society both economically and environmentally." (Malhotra et al. 2013, p. 1265)

Contribution: Ten out of 21 contributions develop theoretical frameworks, e.g., for assessing the impact of organizational goals for Green IS or for generating an ecological economic framework (Faucheux and Nicolaï 2011). Others elaborate theoretical propositions (e.g., Corbett 2013a). Several aim to contribute to future research, e.g., by outlining key issues to address, such as "What is environmental sustainability?" (Elliott 2014). Seidel et al. (2013) provide a theoretical model of the functional benefits that Green IS should offer to enable sustainable organizational practice. In this manner, the authors also consider the material properties required to, e.g., present environmental indicators, provide data analysis mechanisms, and grant access to information and the possibility for configuration and communication.

Finally, the majority of the case studies that we retrieved use their empirical findings to support the preliminary hypothesis or to test the theoretical propositions (Corbett 2013a, 2013b; Ryoo and Koo 2013).

2.2 Evaluation of the Current Status of Research on Green IS: Toward a Sociomaterial Perspective

For all of its merits, the literature on Green IS leaves much to be desired. Our in-depth case study addresses the following limitations of the current research on Green IS.

First, the current research on Green IS and environmental sustainability has yet to consider the more recent conceptualizations of technology (see Mazmanian et al. 2014 for an example). The research program on sociomateriality (Cecez-Kecmanovic et al. 2014; Orlikowski and Scott 2008; Scott and Orlikowski 2010) offers a valuable tool to address the entanglement between technology, work, and knowledge "to generate deep insights into the contemporary world" (Orlikowski and Scott 2008, p. 465). The relevance of a sociomaterial perspective in Green IS is the commitment to a *performative* understanding of the interplay of technology, work, and knowledge (Cecez-Kecmanovic et al. 2014; Jones 2014; Orlikowski and Scott 2008). Sociomateriality underscores how technology cannot be explained as either only social or material but rather as emerging from the co-constitution of socially constructed meanings and material enactments (Orlikowski and Scott 2008). What this perspective entails for the Green IS agenda is that technology-mediated representations of the environment are not given; rather, they are re-presentations and thus anything but neutral. In the case of subsea environmental monitoring, technologies transform natural reality into discrete phenomena that emerge at the intersection between the physical materiality of marine ecosystems, that of the instruments, and the competence of human operators in interpreting the datasets. In this process, the environment is necessarily and purposefully represented through relevant and abstracted features (see, e.g., Monteiro et al. 2012; Østerlie et al. 2012).

Second, we supplement the lack of in-depth case studies and the artifact-centered bias with one based on the perspective of information infrastructure (Constantinides and Barrett 2014; Hanseth and Lyytinen 2010; Monteiro et al. 2013; Tilson et al. 2010; Vaast and Walsham 2009; Williams and Pollock 2012; Yoo et al. 2010). Broadly speaking, an information infrastructure can be defined as a shared, unbounded, heterogeneous, and dynamically evolving sociotechnical system (Hanseth and Lyytinen 2010; see also Monteiro et al. 2013). An information infrastructure perspective in IS thus entails that information systems are distributed, interacting, interconnected, and evolving (Star and Ruhleder 1996; Bowker and Star 1999). Of particular importance in our case are the ongoing configurations of the entire array of sensors, communication networks, databases, and tools for analysis and visualization that support the new capacity for real-time subsea environmental monitoring. Infrastructures provide the means to generate a global coherence to organizations beyond the specificities of local contexts while simultaneously providing the resources to situated practices (Star and Ruhleder 1996; Vaast and Walsham 2009).

Therefore, an infrastructure-turn (Tilson et al. 2010) allows us to unearth the evolving sociotechnical relations across time and contexts that would otherwise be taken for granted (Williams and Pollock 2012).

2. RESEARCH METHOD

3.1 Approach, Access, and Context

The empirical vignettes we present in this paper are drawn from a longitudinal (April 2012 – December 2014) interpretive case study (Klein and Myers 1999) conducted with an ethnographic method (Myers 1999). We obtained access to NorthOil's research center in Norway through a member of our research team who also holds a position in NorthOil as a full-time project manager. The driver for our investigation was NorthOil's involvement since the mid-2000s in several projects to develop tools and work practices to integrate real-time environmental monitoring programs with all of the phases of the lifecycle of a well (exploration, planning, drilling, production, demobilization) in different geographical areas of the world. The environmental monitoring initiatives either occurred at the same time of our study or had been recently concluded.

NorthOil (a pseudonym) is an international oil and gas company headquartered in Norway with more than 20,000 employees worldwide. The oil and gas industry is a dominant sector in Norway. It currently accounts for 20% of the country's GDP, 30% of total investments, and nearly 50% of the total exports (MPE 2014). It operates offshore and is the result of a gradual evolution that relied initially on foreign expertise but has always been focused on developing an internal technological expertise and knowledge base.

The high taxes on CO_2 emissions, together with the high cost of labor and the need to accommodate a dynamic business reality, underpins the concerns of how to improve efficiency (Norsk olje og gass 2005; Rosendahl and Hepsø 2013). Over the last two decades, NorthOil invested heavily in technological innovations, including installing fiber-optic cables to connect offshore sites between them and with the shore; promoting more efficient collaboration, for instance, through video conference systems and integrated work processes; and introducing new simulation and monitoring tools.

Accidents such as the blowout in the Gulf of Mexico in 2010 vividly demonstrate the risks tied to disasters (OSC 2011). Beyond disasters, daily routine operations also impact marine ecosystems. Everyday practices, not only dramatic events, influence the marine environment and warrant scrutiny (Blanchard et al. 2014; Hauge et al. 2014).

The oil and gas sector has a strained relationship and history with environmental concerns. In the Norwegian context, the tensions and conflicts with the fishing industry as well as broader environmental concerns have existed since the inception of oil and gas activities in the late 1960s. Presently, the inherent conflicts are actualized by the ongoing controversy over whether to allow oil and gas operations in new areas in the Arctic North. These areas, the oil industry argues, are particularly interesting geologically, but they are also where the most commercially important fishing takes place. However, the Norwegian continental shelf is home to the world's largest number of cold-water coral reefs (Fosså et al. 2002). The particles, muds, or possible leaks of oil, gas, or water generated while drilling a borehole can spread far away following the water currents and damage the reefs. As a well is later secured for the start of production, small leakages can still occur that are hardly noticeable. Spills and leakages have a more severe impact given the vulnerable marine environment of the Arctic. The Arctic simultaneously holds an estimated 20-25% of the global unexplored oil reserves (Bird et al. 2008). With a retracting ice barrier, new areas become accessible (DOI 2013). Additionally, areas outside the Arctic also face significant environmental challenges. For instance, the areas outside the Brazilian coasts where NorthOil also operates are often characterized by low pressure and heavy oil. This implies that operators produce much water and use 50% more energy on average (thus emitting more CO_2) to recover the oil there from the subsurface reservoirs.

Traditionally, environmental monitoring practices have been labor intensive (involving hired contractors to conduct sampling from vessels) and time consuming (months), and they produce information that is cumbersome to access (in separate databases not integrated with remaining tools). Samples of, e.g., biomass (fish, fish eggs, and zooplankton) are taken to shore to be analyzed in laboratories.

Recent regulations in Norway underscore a continuous and integrated approach to the monitoring of the environment in contrast to traditional, batch-oriented approaches so that "*[s]ufficient information shall be obtained to ensure that all pollution caused by own activities is detected, mapped, assessed and notified, so that necessary measures can be implemented*."[1] In addition to the physical sampling of the seafloor, the specifications of this norm require the remote monitoring of offshore activities, i.e., that data are gathered on the operational site and visualized onshore. In sum, authorities are pushing for a change, but, in the words of an experienced project manager from a consultancy company, every operation is different: "*It depends on the operation (...) [E]very drilling operation is unique.*"

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[1] http://www.psa.no/framework-hse/category403.html#p48; accessed March 2, 2015

We report from the efforts headed by NorthOil in collaboration with service companies and research institutions to set up an information infrastructure for a real-time subsea environmental monitoring capacity.

The two main partners involved in NorthOil's initiatives are the Quality Certification Body (QCB; a pseudonym) – an international organization providing quality certification and environmental risk assessment services – and the Norwegian Institute for Marine Research (IMR), with an established expertise in marine biology but an opposite agenda of demonstrating that oil and gas operations should not be allowed in sensitive ecosystems, such as the High North (Blanchard et al. 2014; Hauge et al. 2014).

We present the results from three different phases of the lifecycle of a well (see Figure 1): *planning* in an area still off-limits to operations; *drilling* a new well in a field densely populated with coral reefs; and *oil production* in a recently acquired field with previously unknown natural conditions.

-- FIGURE 1 about here --

3.2 Data Collection

Our data collection methods consisted of observations, interviews, informal conversations, and documentation mainly gathered by the first author and occasionally assisted by the second author.

The primary source is participant observations. The first author conducted the fieldwork three days a week on average in the period April 2012–April 2014 and one day a week in the period June 2014–December 2014. The primary setting was an office with five NorthOil employees involved in the environmental monitoring projects at the company's R&D department. This proximity provided a useful backdrop to identify employees who we could shadow and follow into internal meetings and workshops or seminars with technology vendors or partner companies. We also travelled to the headquarters of NorthOil and the partner companies on a number of occasions to participate in meetings and workshops. As the familiarity with the research setting improved, the first author was invited to provide feedback about document drafts and other smaller tasks. We underline the importance of participant observations in line with Klein and Myers' (1999) criterion recognizing that data in interpretive research are generated through the social interaction between researchers and the subjects.

Through observations, we identified informants to interview. When possible, we selected people who had taken part in environmental monitoring programs from their inception in different contexts. We asked the interviewees to trace the trajectories of NorthOil environmental programs, narrate their experiences, and reflect on the lessons learned. They provided us with insightful and long narratives of their involvement and the (un)expected events and practices that have characterized each monitoring program. On a few occasions, we could interview two people at a time, which triggered reflections and discussions around the motivations and temporal trajectory of events that occurred up to ten years before the interview. Interviews were also necessary to clarify the content of software or documentation that we could not understand. Alongside interviews and observations, we were often engaged in informal chats with several informants in the office during coffee breaks or at lunchtime.

Finally, we were granted access to current and historical internal documentation, and we could test the software for modeling or visualizing environmental data streams. The historical documentation, together with the actors' narratives, was instrumental to obtain better insight of the case study's broader social, normative, and historical setting – see also Klein and Myers' (1999) principle of contextualization.

-- TABLE 2 about here –

3.3 Data Analysis

Although we are trained and experienced in qualitative research methods with an emphasis on a grounded, inductive approach (references suppressed for anonymity), the data analysis for this paper differed from our previous studies. It had strong deductive elements. While we were immersed in the data collection in our case on real-time environmental monitoring (Klein and Myers 1999; Walsham 1995), we started reading the discourse on Green IS. Driven by a clear sense that our case study did not fit, our data analysis took the form of a stepwise clarification of *how, where, and why our case differed from the contributions within Green IS*.

For instance, the prevalence of studies in Green IS that consider both technology and the environment as fixed struck us as at odds with ongoing debates about how to conceptualize the IT artifact (Orlikowski and Iacono 2001). Recently, this debate has evolved around sociomateriality which is, at a minimum, committed to portraying technology as mutually constitutive with its use (Jones 2014). Influenced by our prior experience with this theoretical stream (references suppressed for anonymity), we were struck by the complete absence of anything related to sociomateriality in Green IS; thus, we made it one of our two key constructs.

Similarly, the artifact-centric preoccupation present in Green IS with smart meters, content management systems, or emission tracking tools differed radically from the collection and interaction of sensors, analysis tools, networking capabilities, and visualization systems characterizing our study. There were no singular artifacts that 'did' real-time environmental monitoring; rather, it was the collection of artifacts. Our history of engagement with research on information infrastructure led us to consider this as our second construct (references suppressed for anonymity).

Through theoretical sampling (Suddaby 2006), we purposely selected three empirical vignettes spanning the phases of the lifecycle of an oil well to demonstrate that environmental sustainability around our two constructs (i) is pragmatically performed as an evolving sociomaterial process and (ii) unfolds in practice as an information infrastructure. The three empirical phases underpin the presentation of our empirical findings in the next section.

3. EMPIRICAL FINDINGS

4.1 Planning for Drilling in North Norway: Classifying the Water Column

In this section, we present NorthOil's environmental monitoring activities preliminary to the decision by the authorities to open an area to oil and gas operations. The ocean outside North Norway, particularly offshore the Lofoten Islands, is the only portion of the Norwegian continental shelf that is currently forbidden to oil and gas operations due to its environmental diversity and because the continental shelf is at its narrowest at that point. It is an area rich in coral reefs and a spawning area for commercial species of fish (notably cod and herring), which migrate there to leave their eggs from January to April. However, debates on the possibility to open the area to oil and gas exploration have recently inflamed the Norwegian political arena.

We present this example as a case where hardware devices, software models, and work practices must be entangled and tuned to discover and classify a fairly unknown portion of the ocean.

In the second half of the 2000s, NorthOil embarked on an underwater monitoring program in the area. Initially part of an EU-funded research project, the strategic business nature of the monitoring program did not go unnoticed by NorthOil's department of field production and development, which decided to provide financial support in 2011. Had the Norwegian government opened the area for oil and gas operations, the company would have been better positioned than its competitors to propose a proactive approach to environmental risk assessment. The monitoring activity is facilitated by the deployment of a rather simple network of off-the-shelf sensors on the sea floor placed less than half a kilometer off the coast. In addition to devices to measure the pressure, temperature, and salinity and cloudiness of the waters, acoustic sensors are used to detect moving biomass in the water column. The sensors were installed on a semi-pyramidal metallic structure weighing 400 kg connected to a 1.8 m-tall satellite crane via a 50 m subsea cable. Additionally, a camera with a flash was placed on the crane to spot a coral reef previously identified by environmental experts. In 2013, the sensor network was connected to an onshore data center through a 400 m-long fiber-optic cable. Both the installation of the sensors and the fiber-optic cable went through a number of maintenance and repair rounds. As we were told by several project participants, these rounds were always more cumbersome than expected, particularly because North Norway is characterized by rough weather conditions and the sea floor is affected by landslides.

As real-time data began to be fed to shore through the cable, they were the only actual real-time environmental data of high quality flowing into NorthOil's databases. As a result, they were released to QCB to develop a methodology for dynamically monitoring and classifying the amount of biomass in the water column. Nearly all of the parameters measured by the North Norway observatory became involved in the water column classification system. In particular, the acoustic sensors work by sending a signal – an acoustic wave – and measuring the wave returned as an echo as their signal hits a target (e.g., a fish such as cod or herring). These data are matched with other parameters measured simultaneously (e.g., temperature, salinity) through a mathematical formula where every value is multiplied by an experience-based parameter to weight the credibility of the corresponding sensor.

The idea of classifying the biomass was driven by the observation that telling an indefinite audience that the concentration of biomass at 1:12 AM on March 6th at a given point is "-73.20 dB" [decibels] at a depth of 75 m is not necessarily informative. Thus, the mathematical formulas should be turned into a simpler language familiar to the disciplines used to risk assessment practices (e.g., drilling engineers). In need for a solution to present the measurements without requiring expertise in acoustics, QCB engineered the environmental value, a number expressed in decibels to summarize the hourly concentration of biomass in larger cubes of the water column (e.g., from -50 m to -75 m). The environmental value is obtained by collapsing a few of the original sections scanned by the acoustic devices into one. This strategy enhanced not only the visualization but also the storing of biomass data, generating considerably fewer data entries every hour instead of seconds. Stemming from the environmental values of each water cube, QCB developed a categorization structure based on five colors to classify the amount of biomass from lowest to highest (see Figure 2). QCB's methodology is admittedly not entirely new. It takes inspiration from an approach by the Norwegian Directorate of the Environment[2]. However, in addition to providing environmental resource maps with higher resolution, it is novel in the fact that it is based on the data series collected by an oil and gas company.

However, QCB's concentration categories per se are rather uninformative. They are always relative because they are generated by comparing the current biomass concentration with the concentration that is *expected* to be found at a specific time of the year. The expected concentration is obtained by collecting datasets for several consecutive years to define what is normal and what constitutes a deviation from normality. The side effect of a relative measure is that it is difficult to compare with measures taken elsewhere. Two fish spotted in North Norway during the spawning season might indicate a low concentration, whereas two fish in an area that is typically deserted might be classified as a high concentration.

-- FIGURE 2 about here –

4.2 Drilling Offshore Central Norway: Monitoring the Coral Reefs

Drilling a new well to extract oil or natural gas is a critical operation. As required by authorities, environmental risk must be assessed before and during the drilling phase. The majority of the assessment is carried out via simulation models that predict the dispersion of potentially polluting materials. What should or should not be included in the models is always a difficult choice and is the result of situated and experience-based judgments that are fed into seemingly quantitative reports and plans.

As opposed to North Norway, oil and gas activities are fervent in the Norwegian Sea offshore Central Norway. Cold-water corals are dense in the Norwegian waters at depths ranging from 30 to 3,000 m (Fosså et al. 2002). The coral reefs can build even 3 m-high structures, feed off plankton, and become the center of a heterogeneous set of fish, crustaceans, and sponges. The Norwegian environmental authorities constrain oil and gas companies to have their drilling plan approved before they can actually embark on drilling a new well close to the reefs.

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[2] www.havmiljø.no. Accessed March 2nd, 2015

When the new well is drilled, particles of a heterogeneous nature spread, generating a moving cloud of particles in the water column. The particles can also settle on the corals and seafloor. These events must be forecast by the oil and gas company willing to obtain permission to drill a new well. A drilling plan describing the environmental resources in the area around the proposed drilling location and the predicted amount and diffusion of the particles generated must be issued to the authorities. However, defining the area to monitor around the drilling location is the result of experience and expertise; there is a lack of precise guidelines on how to set its boundaries. QCB has recently developed a best-practice approach that has been adopted by the Norwegian Oil and Gas Association and thus incorporated into NorthOil monitoring programs.

Risk is embedded in the choices made about what to measure and what not to measure. As a QCB coral expert explains:

> "*And we know something about the distances that [the particle cloud travels] in general, and its components, (...) the footprint of such a plume. (...) Or, in this case [pointing at a sketch of the sea floor he is drawing] we know that we don't have to sample 1000 meters away. That's meaningless. Maybe 100, 200, 300 m or something. So, I mean, then you are narrowing it down based on knowledge (...) And in addition, for instance, if this is a* ***good coral structure*** *and we know it is less than 50 m away from the drilling location, we know that this structure may receive sedimentation. So, in a risk way of thinking, we may say that this may be at risk. While this, which is 500 m away, we don't bother so much. (...) So, in that sense, it is a little bit risk based as well, how you monitor it."*

Moreover, not all coral structures are affected by sedimentation and turbidity in the same way. Their probability of been harmed is directly proportional to their position relative to the particle cloud generated when drilling and to their health (i.e., a dead coral structure will not be further affected). The definition of the health of a coral is what the previous interviewee implied when speaking of "a good coral structure." He elaborates further:

> "*Corals in Norway are today [classified into] 4 classes, so you are putting some value on your resource. And that's important for us, and if you want to do risky you need to value resources, and corals are valued into four classes more or less, and that's based on area, height, and also the size (...). Dead [corals] we forget*."

Cryptic statements such as "*in a risk way of thinking*," "*this may be at risk*," and "*if you want to do risky you need to value resources*" indicate that the assessment of the environmental sustainability of oil and gas operations must go through a sequence of quantification steps to present environmental information in the language of 'risk' – one that is familiar to, e.g., the drilling engineers who are formally constrained to ‘put a value’ on the risk of their activities. The ‘value’ for each coral structure is then mapped in a risk matrix, a simple 4×4 table, in which the expected probability of pollution is indicated on the y-axis and its consequence is indicated on the x-axis (Figure 3). Each cell is filled with intuitive colors (green, yellow, orange, and red) to signal the level of danger associated with each possible probability/consequence combination. The risk value for a coral structure is pinpointed inside one of the cells.

-- FIGURE 3 about here –

NorthOil was collaborating with QCB to turn this methodology used during the planning phase into an online methodology also to be used during the drilling phase. The reason is that the particle cloud can change considerably when drilling occurs. For example, the currents might change and take the particles elsewhere than originally forecast, or the particles might aggregate and form a crater close to the borehole, resulting in a smaller cloud in the water. The risk matrix is a powerful tool for representing and comparing the heterogeneous combinations of predicted pollution and coral reefs into a standardized language, but it cannot account for unpredictable situated events. Thus, the results of risk assessment methods must always be interpreted based on the knowledge of a situated context. The environmental expert quoted above explains why knowledge of the environmental conditions in one area tells almost nothing about other areas:

> “*Each area can be very different. Even if we used the [North Norway] data where we have no activities, it is difficult to compare [North Norway] to [Central Norway]. (...) It has to do with the types of sediments, for example, which types of particles, which sea floor you have in [North Norway] versus [Central Norway] (...). And there can be yearly variations in relation with natural sedimentation, in the spring there is likely more plankton, phytoplankton, etc. And it can be very different also in relation to depth, depending on many things*.”

4.3 Oil Production Offshore Brazil: Monitoring the Calcareous Algae

In this paragraph, we present the underwater environmental monitoring program established by NorthOil during the production phase in a newly acquired field offshore Brazil.

In the late 2000s, NorthOil acquired a deep-water oil field offshore the southern coast of Brazil. It was intended to be operated 50% by another company, whose share was purchased by NorthOil some months after the development of the facility had begun. NorthOil initiated another environmental monitoring program in this field in 2009 nearly simultaneously with the two Norwegian programs. Another set of sensors, highly similar to those installed in North Norway, was sent out to monitor the underwater environment around an operational field recently acquired by NorthOil. The sensors were placed nearby the oil extraction platform to look at the possible oil leakages. In this instance, the data were not sent onshore in real time but rather stored in hard disks placed in the same structure as the corals. What the environmental experts at NorthOil soon discovered was that the Brazilian waters are highly different from the Norwegian waters: they are warmer and more saline and have stronger currents. Moreover, instead of corals, the sea floor is populated by calcareous algae. These two environmental resources are extremely different: whereas corals are animals, algae are plants, and as such, they need light to reach them to grow. Thus, water turbidity is an issue to be prioritized when monitoring at that location, as it might prevent the light from reaching the algae. In addition, algae are the size of a golf ball, whereas corals can build structures of up to 20 m. Therefore, in the Brazilian field, there was no need to install a satellite crane to position the camera, which could take pictures of the algae directly from the sea floor.

However, the first monitoring attempts were a failure. One of the environmental advisors responsible for the campaign told us:

> "*But it did not go so well, we got a little damage on it so it registered data only for a short period, and then the batteries ran out, really a short circuit (...) So we did not get any good data from that period either (...) Part of the reason was that we went out of energy, another was that the sensors did not work as they should have then, so there was a deal of problems with corrosion and short circuits because the environment in [Brazil] is extremely corrosive. We had not taken that into account*."

The advisor's account indicated that the Brazilian waters are more corrosive than initially expected by NorthOil's environmental experts. Failing to account for aspect caused a number of technical failures that did not allow the program to gather sufficiently good data streams. As a countermeasure, the support structure was rebuilt in titanium and designed such that all sensors were more protected from the current. However, after several additional attempts, the data collection began to work and "*we got loads of good data*."

What the Brazilian campaign taught NorthOil was actually a broader lesson. The failure of the first environmental monitoring attempts turned the company's attention to the nearby oil platform. The side effect of the environmental data collection was indeed the discovery of the corrosive effect of the waters in the area – a phenomenon that would otherwise remain unnoticed and cause accidents on the platform in the long run. In fact, in the Brazilian case, environmental monitoring is strongly related to safety. Given that another company had planned the platform, the importance of careful environmental monitoring in relation to the business choices is also emphasized. We discussed this topic during one interview with two of the environmental advisors responsible for the Brazilian monitoring program:

> *Interviewee 1: "It came as a big surprise for the whole organization, so we have conducted massive reinforcements or measures in relation to the platform which stands there. It's a little stupid if the platform suddenly disappears!"*
> *Interviewee 2: "The current strength is a problem because the platform is designed for a lower current than the real one. There was no measurement of current in [that field] before"*
> *[...]*
> *I1: "[It is a] typical example that (...) shows a very special example of the extreme need to have good meteorological and oceanographic data before you go in. One thing is in a way the environmental measurements, but in relation to the safety part, it is totally essential. And there were not good measurements of this before we came in with our project and that is not good."*

4. DISCUSSION

5.1 A Sociomaterial Lens on Environmental Monitoring

The immediate and important implication of adopting a sociomaterial perspective on subsea environmental monitoring is to underscore the *constructed* nature of representations of the environment. They are anything but neutral, but they turn nature/the environment into an ordered 'fact' for professional audiences (cf. Porter 1996). The representations of the environment are neither complete nor accurate but serve purposes related to situated tasks or problem solving (Edwards 1999), e.g., allowing engineers to answer such questions as "Is it safe to drill here?" We analyze the material circumstances of fact production regarding the subsea environment; what these facts state invariably involves the material/technological means by which they are known. In summary, what we know is how we know it (cf. Østerlie et al. 2012). We focus specifically on NorthOil's *selection* of what aspects of the environment to articulate and how this subsequently becomes *abstracted* into a language compatible with risk assessments.

First, features of the corals are *selected* to fit the language of the risk matrix (see Figure 4). Selection is a constitutive part of the quantification process (Porter 1996). Sensing devices, cameras, cables, databases, and modeling software make this translation possible and filter out undifferentiated nature by selecting discrete features. To calculate the risk associated with the drilling of a new well, the marine ecosystem is turned into a bounded area by relying on previously acquired expertise ("*you are narrowing it down based on knowledge*") (cf. Almklov et al. 2014). Corals are classified into discrete conditions (good, damaged, or dead). Their health is assessed by experts through an assessment of the available data (i.e., pictures taken every 30 min). The ecosystem of marine animals and flora that live in a coral structure is funneled into this assessment process and summarized as part of the coral. Similar to corals, the water mass is calculated in and through the sensors turned into environmental values. The open-ended ecosystem is reduced by selecting the 'water column,' which is further divided into sections depending on the scanning capabilities of the acoustic sensors.

Instrument-enabled selection is performative in defining what counts as 'the environment.' As the coral expert quoted in section 4.2 explains: "*dead [corals] we forget*." If a coral is assessed to be dead, it can no longer be classified as being at risk: you cannot harm what is already dead – even though it might still be useful to the surrounding ecosystem. Because dead corals do not fit into the risk picture, they are filtered out. The same situation occurs when QCB experts define the opposite of a dead coral, i.e., a "*good coral structure*" that might be affected by the drilling operations. However, if it is assessed to be sufficiently far from the drilling point, it is also filtered out.

Second, environmental phenomena are *abstracted* into a risk language recognized by oil and gas professionals. New units of analysis (a portion of the water column; a coral structure) summarize the complexity of a submarine ecosystem to make it recognizable to professionals accustomed to similar unities of measure when they must detect, e.g., oil leakages. In the case of coral risk assessment, after an examination by an environmental expert, the pictures of the corals are transformed into a color label to describe the coral's health status, and finally, a numeric value is stamped onto the risk matrix referring to the predicted drilling discharges. A similar process characterizes the definition of the environmental value resulting from a mathematical formula to summarize the dynamic fish traffic in a portion of the water column.

The environmental value and risk matrix are performed as part of the sociomaterial practices, including the natural resources, technologies, regulations for environmental monitoring, and experience of experts in interpreting the results. These measures cannot be disentangled from the monitoring machinery and the location where they were taken. For instance, the environmental value is calculated *relative* to the historical trend of biomass concentration in that specific area; hence, it acquires a different meaning at different sites. Thus, environmental monitoring resonates with the material specificity of the sensor arrangements and that of the ecosystems themselves. The types of sediment, particles, composition of the seafloor and weather conditions vary dramatically, as do the seasonal variations. These variations must be accounted for when interpreting the monitoring results. This necessity was made clear when NorthOil's environmental advisors deployed the North Norway monitoring infrastructure in the Brazilian waters. The natural conditions of these waters were so different from the Norwegian setting that the experts were initially caught by surprise. First, the corrosive waters irreversibly damaged the monitoring equipment, urging to adopt a titanium supporting structure and to re-position the sensors so that they would be protected from the water flow. A second problem was the difference between the calcareous algae and corals. Given the algae's need for light to live, water turbidity became a fundamental parameter in the Brazilian monitoring program – something that was not considered as relevant in North Norway where no operations were conducted and where corals do not depend on sunlight to grow.

5.2 An Infrastructure-Turn for Environmental Sustainability

NorthOil's subsea environmental monitoring machinery encompasses networks of *interconnected* remote sensors (e.g., acoustic sensors, subsea cameras, light sensors), data transfer mechanisms, desktop systems (e.g., risk matrices, environmental values, particle spreading modeling software), and formal work processes spread across different geographical locations (e.g., North Norway, Central Norway, Brazil). Environmental monitoring is performed in and through this large-scale technical 'apparatus' (see, e.g., Jones 2014) rather than any singular artifact. We maintain that information infrastructure is a powerful analytical tool to unravel how the sociomaterial process to turn nature into facts emerges out of the digitally mediated *interactions* between humans, technologies, and the monitoring location (Williams and Pollock 2012; Monteiro et al. 2013; cf. Almklov et al. 2014; Østerlie et al. 2012).

The interactivity and interconnectedness of infrastructure are the reason why every action at one point is connected with and has consequences that occur elsewhere. One example is the connection between the environmental monitoring campaigns in North Norway and Brazil. NorthOil approached the monitoring of the latter area that was previously unknown to its environmental experts by repurposing the same machinery adopted in North Norway. The Brazilian experience eventually had a ripple effect across all of the fields operated by NorthOil throughout the world because it triggered an understanding of environmental monitoring as related to operational safety. In this process, different spatial scales are entangled but must coexist for environmental monitoring to be conducted successfully. An infrastructure works only when it has the ability to balance situated needs while simultaneously stretching across geographical boundaries (Star and Ruhleder 1996).

The subsea observatories are themselves an example of the ability of infrastructure to address the geographical dimension. The environmental experts configured the monitoring stations to make them representative of an area that is as wide as possible. The approach was to achieve the most out of the interactive and interconnected properties of the infrastructure. For instance, the scope of the acoustic sensors is combined with the scope of other sensors to synthetize a geographical area and to calculate the environmental value. This aspect was also clear in Brazil. There, the configuration was complicated by the fact that the monitoring campaign was run in a different operational phase than in North Norway.

Thus, NorthOil's approach to the environmental monitoring infrastructure, through a number of adaptations and reconfigurations, is able to stretch across different locations and different operational phases. The tools, sensors, and various information technologies remain interconnected but are made to interact differently relative to the purpose at hand.

Another reason why NorthOil's approach unfolds as an infrastructure is that it does not only involve NorthOil. To be precise, what appears to be NorthOil's environmental monitoring approach is actually the result of the long-term work of at least other two key players: QCB and the IMR – in addition to several technology vendors. The monitoring infrastructure allows for the purposeful combination of the different experiences and agendas of these three players.

The features of NorthOil's real-time environmental monitoring infrastructure described above are well synthetized into the story of the environmental value. Its development occurs across many locations and companies and over a long time span. It demonstrates how an artifact such as the North Norway ocean observatory cannot be understood outside its institutional and technological setting. Consider again the environmental value. From its inception, it was rooted into the recurring debates in the Norwegian politics regarding the possibility of opening the areas offshore North Norway, thus motivating NorthOil's and consequently QCB's investments in a project to gather the knowledge base of a marine ecosystem. It also motivates the enrollment of the IMR due to its deep-seated experience in marine biology despite its opposition to NorthOil's goals of obtaining an opening in North Norway (cf. Blanchard et al. 2014).

Then, the environmental value on the seafloor results from the interactions among specific sensors provided by external vendors. These sensors are often the subsea adaptation of sensors that fishermen regularly use to detect fish from their boats. The capabilities of these sensors shape the final result, but their development occurs elsewhere and is largely outside the control of either NorthOil or QCB. The sensor measurements are finally combined into a mathematical formula that weights the trustworthiness of every measurement based on the experience of their behavior and the trend followed by the parameters they measure. This approach is made possible only by the long-term experience acquired by different experts of the behavior of those specific devices. However, this experience is also not under the control of NorthOil or QCB and can be sought by leveraging external existing infrastructures, such as the datasets collected by fishermen from their boats when searching for fish.

The aspects we have just described display the recursivity that is typical of information infrastructures (Hanseth and Lyytinen 2010). Recursivity is due to the constant reconfiguration of the characteristics of interconnectedness, interactivity, and distribution. In the Brazilian experience, for example, the environmental experts uncovered more problems and links as they learned more about the environmental trends in the area. As they understood more about environmental sustainability in the area, they found more dangers and solutions in relation to the corrosive effects of the marine waters for the oil platform. The experts were thus able to promptly re-configure the monitoring station and to understand the relevance of environmental monitoring for assessing technical risk and ensuring human safety. This is another reason why environmental sustainability should be addressed through an infrastructure perspective: infrastructure, unlike specific devices and systems, can acquire multiple functions due to its dynamism and longevity, which are generative of new opportunities for exploration (Tilson et al. 2010).

5. CONCLUSION: THE POLITICS OF GREEN IS

Green IS is an important yet under-developed agenda. Tying Green IS to broader debates in IS research on how to conceptualize the IT artifact (Cecez-Kecmanovic et al. 2014; Orlikowski and Scott 2008) and its increasingly infrastructural qualities (Monteiro et al. 2013; Williams and Pollock 2012) is a way to broaden and hopefully also invigorate the Green IS debate. Highlighting, as we have done, how 'facts' about the inaccessible marine environment are colored by the specific infrastructures that allow for them to emerge (Edwards et al. 2013) immediately opens these 'facts' to political debate. The way facts are produced (literally: manufactured) must be scrutinized as part of the Green IS agenda.

NorthOil's efforts are particularly interesting in this respect because the company is reshuffling the *modus operandi* of the machinery for environmental risk fact production, thus making visible its political meaning and the associated redistribution of resources, labor, and power (Graham and Thrift 2007; cf. Orlikowski and Scott 2008) that the Green IS agenda should take onboard.

NorthOil's case demonstrates that controversy is a necessary part of the process of fact construction. The heated political debates around the possibility of opening the areas offshore North Norway and the Lofoten Islands to oil and gas activities are a case in point. However, NorthOil's approach to address controversies has not been that of solving them but rather to capitalize on them to gather new knowledge about the marine ecosystem. This must be understood in light of the guidelines from the Norwegian government that established a management plan to assess the potential risks offshore North Norway stating that "all management of the natural environment must be knowledge-based" (NME 2011, p. 6).

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Appendix

Literature review methodology

We conducted a systematic literature review to investigate the current status of research within Green IS. The systematic review method is inspired by Dybå and Dyngsøyr (2008).

The details of our approach are provided below.

Step 1) Preliminary settings

Temporal window: Our search spanned the years 2008-2014 (following Malhotra et al. 2013), where 2008 is the year of Watson et al.'s (2008) seminal article raising attention to environmental sustainability as a relevant topic for the IS literature and 2014 (December) is the time of writing.

Research question: We set the following explorative research question: "*What is the state of the art in the Green IS research field?*"

Query definition: After a preliminary explorative search to familiarize ourselves with the vocabulary adopted in Green IS, we set the following query: "Green information systems for environmental sustainability."

Step 2) Identification of relevant studies

Our review was systematic in terms of the method applied. In terms of scope, it was confined to the most impactful publication channels within IS:

1. We searched the basket of leading journals of the Association for Information Systems (AIS): the Management of Information Systems Quarterly, Journal of the Association for Information Systems, Business & Information Systems Engineering, and Communication of the Association for Information Systems.
2. We queried the ISI Web of knowledge and Google Scholar to seek additional relevant papers we could have missed or which are published elsewhere.
3. We browsed the references cited by the papers retrieved to identify additional relevant studies.
4. We finally browsed the proceedings of the main IS conferences (ICIS, ECIS, and AMCIS). In so doing, we also noticed that the tracks dedicated to Green IS have been constantly present in the last years under labels such as "Sustainably digital"

(ECIS 2014), "Green IS and sustainability" (AMICS 2013 and 2014) or "Green IS and sustainability" (ICIS 2013).

We stored and managed our results through the Zotero citation manager plugin for Firefox.

Step 3) Critical appraisal of papers

We then selected the articles that were eligible for inclusion in our review. We conducted a filtering process and browsed (in sequence) each article's title, abstract, and full text. At each step, articles were excluded if they did not meet the criteria of relevance (i.e., to be a contribution to the IS community).

After a duplicate removal step, we were left with n = 21 primary studies, mainly from journals (see list below).

Step 4) Article classification

Finally, we coded the articles to classify them based on a classification scheme along the three main features of a research article:

- Contribution provided ("*What has been discovered that was not known before?*");
- Unit of analysis ("*What is being studied?*");
- Research method ("*How has the study been conducted?*").

The articles have been mapped according to these categories as shown in Table 1.

List of references to the articles considered

Bengtsson, F., and Ågerfalk, P. J. 2011. "Information technology as a change actant in sustainability innovation: Insights from Uppsala," *The Journal of Strategic Information Systems* The Greening of IT (20:1), pp. 96–112.

Bose, R., and Luo, X. 2011. "Integrative framework for assessing firms' potential to undertake Green IT initiatives via virtualization – A theoretical perspective," *The Journal of Strategic Information Systems* The Greening of IT (20:1), pp. 38–54.

Butler, T. 2011. "Compliance with institutional imperatives on environmental sustainability: Building theory on the role of Green IS," *The Journal of Strategic Information Systems* The Greening of IT (20:1), pp. 6–26.

Chasin, F. 2014. "Sustainability: Are We All Talking About the Same Thing?," in *2nd International Conference on ICT for Sustainability (ICT4S 2014)*.

Chen, A., Watson, R., Boudreau, M.-C., and Karahanna, E. 2009. "Organizational Adoption of Green IS & IT: An Institutional Perspective," *ICIS 2009 Proceedings*.

Chowdhury, G. 2012. “Building environmentally sustainable information services: A green is research agenda,” *Journal of the American Society for Information Science and Technology* (63:4), pp. 633–647.

Corbett, J. 2013a. “Designing and Using Carbon Management Systems to Promote Ecologically Responsible Behaviors,” *Journal of the Association for Information Systems* (14:7).

Corbett, J. 2013b. “Using information systems to improve energy efficiency: Do smart meters make a difference?,” *Information Systems Frontiers* (15:5), pp. 747–760.

Dao, V., Langella, I., and Carbo, J. 2011. “From green to sustainability: Information Technology and an integrated sustainability framework,” *The Journal of Strategic Information Systems* The Greening of IT (20:1), pp. 63–79.

Elliot, S. 2011. “Transdisciplinary Perspectives on Environmental Sustainability: A Resource Base and Framework for IT-Enabled Business Transformation,” *Management Information Systems Quarterly* (35:1), pp. 197–236.

Faucheux, S., and Nicolaï, I. 2011. “IT for green and green IT: A proposed typology of eco-innovation,” *Ecological Economics* Special Section - Earth System Governance: Accountability and Legitimacy (70:11), pp. 2020–2027.

Hilpert, D.-W.-I. H., Kranz, P. D. J., and Schumann, P. D. M. 2013. “Leveraging Green IS in Logistics,” *Business & Information Systems Engineering* (5:5), pp. 315–325.

Jenkin, T. A., Webster, J., and McShane, L. 2011. “An agenda for ‘Green’ information technology and systems research,” *Information and Organization* (21:1), pp. 17–40.

Loock, C.-M., Staake, T., and Thiesse, F. 2013. “Motivating Energy-Efficient Behavior with Green IS: An Investigation of Goal Setting and the Role of Defaults,” *Management Information Systems Quarterly* (37:4), pp. 1313–1332.

Malhotra, A., Melville, N., and Watson, R. T. 2013. “Spurring Impactful Research on Information Systems for Environmental Sustainability,” *Management Information Systems Quarterly* (37:4), pp. 1265–1274.

Marett, K., Otondo, R., and Taylor, G. 2013. “Assessing the Effects of Benefits and Institutional Influences on the Continued Use of Environmentally Munificent Bypass Systems in Long-Haul Trucking,” *Management Information Systems Quarterly* (37:4), pp. 1301–1312.

Melville, N. 2010. “Information Systems Innovation for Environmental Sustainability,” *Management Information Systems Quarterly* (34:1), pp. 1–21.

Molla, A., and Abareshi, A. 2012. “Organizational Green Motivations for Information Technology: Empirical Study,” *The Journal of Computer Information Systems* (52:3), pp. 92–102.

Ryoo, S. Y., and Koo, C. 2013. “Green practices-IS alignment and environmental performance: The mediating effects of coordination,” *Information Systems Frontiers* (15:5), pp. 799–814.

Seidel, S., Recker, J., and Brocke, J. vom. 2013. “Sensemaking and Sustainable Practicing: Functional Affordances of Information Systems in Green Transformations,” *Management Information Systems Quarterly* (37:4), pp. 1275–1299.

Watson, R., Boudreau, M.-C., and Chen, A. 2010. “Information Systems and Environmentally Sustainable Development: Energy Informatics and New Directions for the IS Community,” *Management Information Systems Quarterly* (34:1), pp. 23–38.

Table 1. Facets of the current literature on Green IS.

	WHAT		HOW		CONTRIBUTION
	Empirical case	User persuasion ?	Research method (if relevant)	Focus on artifacts?	
(Bengtsson and Ågerfalk 2011)	IT for sustainability reporting and assessment in a municipality		Action research		Empirically grounded analysis of the effects of reporting and analysis systems
(Bose and Luo 2011)					Theoretical framework
(Butler 2011)	Compliance-to-Product (C2P) application in IT manufacturers		Explanatory case study		Theoretical framework. Empirical validation of the model.
(Chasin 2014)			Systematic literature review		Literature-based definition of sustainability
(Chen et al. 2009)	Adoption of Green IS and IT in manufacturing and service industries	x	Survey		Motivating product stewardship
(Chowdhury 2012)			Literature review		Proposition to base Green IS on the model of cloud computing
(Corbett 2013a)	Carbon management systems (CMS) in three organizations	x	Positivist case studies	Design and use of CMS	Theoretical framework. Empirical validation of the model.
(Corbett 2013b)			Data from electricity utilities for hypothesis testing	Smart meters	Theoretical propositions of variance in energy efficiency. Empirical validation of the model.
(Dao et al. 2011)				IT resources and integration with supply chain resources	Theoretical framework
(Elliot 2011)			Literature review		Theoretical framework
(Faucheux and Nicolaï 2011)			Literature review		Theoretical framework
(Hilpert et al. 2013)	Greenhouse gas (GHG) emission tracking in logistics		Design science research	GHG artifact	Development and evaluation of a GHG artifact
(Jenkin et al. 2011)		x			Literature-based research framework
(Loock et al. 2013)	Web portal of a utility company to reduce electricity consumption		Web portal analysis; field experiment for hypothesis testing	Households, smart meters	Theoretical framework
(Malhotra et al. 2013)			Literature review		Review of the status of Green IS research. Development of a research agenda.
(Marett et al. 2013)	Intelligent transportation systems (bypass) for trucks	x	Survey		Identification of motivations to adopt Green IS
(Melville 2010)					Theory-grounded propositions of a research agenda.
(Molla and	Carbon consumption in	x	Survey		Identification of motivations to

Abareshi 2012)	Australian organizations				adopt Green IS
(Ryoo and Koo 2013)	Environmental management practices of manufacturers		Survey		Theoretical framework
(Seidel et al. 2013)	Environmentally sustainable business practices in an operating software provider		Interpretive case study	Functional affordances of information systems	Theoretical framework. Better insight into affordances required by sustainable transformation.
(Watson et al. 2010)					Development of a research agenda for Green IS

Table 2. Data collection.

Data source	**Content**
Observations (April 2012-December 2014) • Desk in office with 5 NorthOil employees • 48 meetings (teleconferences, workshops, seminars, briefing sessions) • 36 regular briefing sessions on tasks related to environmental monitoring projects • 14 events (conferences, seminars, workshops) indirectly related to NorthOil's projects. • Coffee and lunch breaks	• General issues emerging in the environmental monitoring projects. • Establishment or modification of data management and work processes. • Enrollment of external or internal stakeholders to take a role in the environmental monitoring procedures. • Possibilities and constraints of subsea sensor networks.
Semi-structured interviews (38) • 17 with NorthOil employees (engineers, environmental experts) participating in different environmental monitoring projects • 4 with NorthOil data management experts participating in related projects • 9 with environmental experts from a service company (QCB) collaborating with NorthOil • 1 with the vice president of another partner company • 2 with NorthOil computer engineers • 3 with marine acoustics experts from a technology vendor • 2 with marine acoustics experts at the Norwegian Institute for Marine Research	Insight on the employee's experience in the company and in the environmental monitoring projects, e.g.: *What is your background and experience? What is your position and role in the company and in the project? What are you currently doing in the projects you are involved in? With whom? What tools are you developing or using?* Historical narratives of the monitoring programs, e.g.: *What environmental monitoring programs have you been involved in? How and why was the program initiated? How did it evolve?*

Documentation - MS SharePoint team sites - Internet-based public information	- Historical and future strategies and policies of NorthOil. - Private emails exchanged internally or with vendors. - Official reports. - Environmental monitoring project deliverables. - Internal notes and presentations.

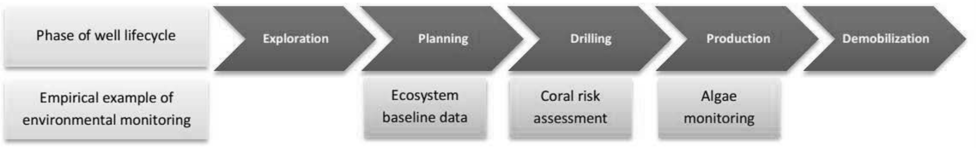
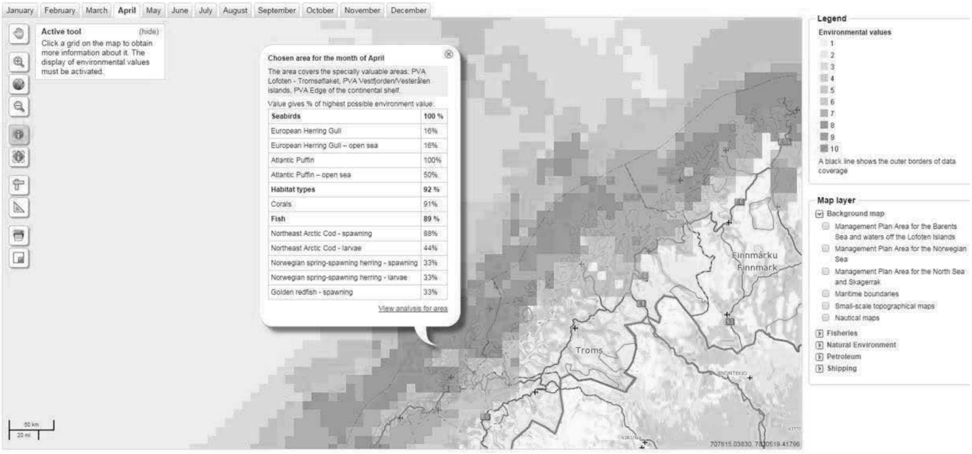


Figure 1. A simplified representation of the most important phases of the oil well lifecycle and the empirical instances of environmental monitoring presented in this article.



Active tool (hide)

Click a grid on the map to obtain more information about it. The display of environmental values must be activated.

Chosen area for the month of April

The area covers the specially valuable areas: PVA Lofoten - Tromsøflaket, PVA Vestfjorden/Vesterålen islands, PVA Edge of the continental shelf.

Value gives % of highest possible environment value:

Seabirds	**100 %**
European Herring Gull	16%
European Herring Gull – open sea	16%
Atlantic Puffin	100%
Atlantic Puffin – open sea	50%
Habitat types	**92 %**
Corals	91%
Fish	**89 %**
Northeast Arctic Cod - spawning	88%
Northeast Arctic Cod - larvae	44%
Norwegian spring-spawning herring - spawning	33%
Norwegian spring-spawning herring - larvae	33%
Golden redfish - spawning	33%

View analysis for area

Legend

Environmental values

1
2
3
4
5
6
7
8
9
10

A black line shows the outer borders of data coverage

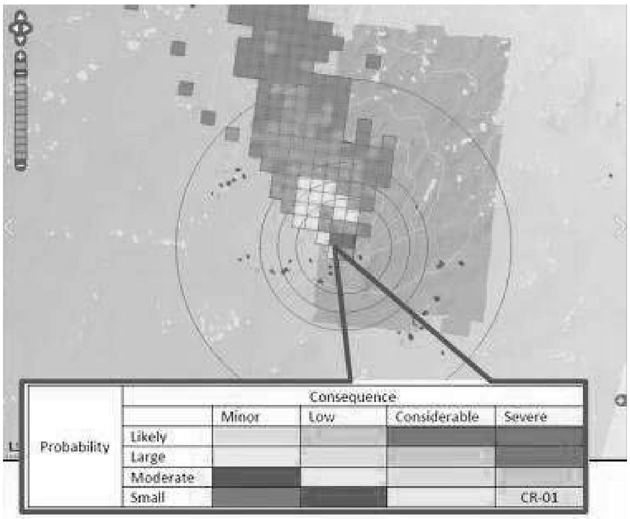
Map layer

- Background map
  - ☐ Management Plan Area for the Barents Sea and waters off the Lofoten Islands
  - ☐ Management Plan Area for the Norwegian Sea
  - ☐ Management Plan Area for the North Sea and Skagerrak
  - ☐ Maritime boundaries
  - ☐ Small-scale topographical maps
  - ☐ Nautical maps
- Fisheries
- Natural Environment
- Petroleum
- Shipping

Figure 2. Environmental values of the sea offshore North Norway (havmiljø.no).

		Consequence			
		Minor	Low	Considerable	Severe
Probability	Likely				
	Large				
	Moderate				
	Small				CR-01

Figure 3. Reproduction of the "risk matrix" incorporated into EnviroTime by QCB in which a severe consequence is predicted for the coral structure labeled "CR-01" against a small probability of being reached by the plume of drill cuttings.



		Consequence			
		Minor	Low	Considerable	Severe
Probability	Likely				
	Large				
	Moderate				
	Small				CR-01

Figure 4. Reproduction of a map of the sea floor, where corals are marked in different colors based on the level of risk (see the red, orange, and green shapes) and the drilling discharge plume is modeled as a cloud of squares colored in different ways based on the risk level for that area (green is minor risk; red is maximum). A risk matrix is assigned to each coral structure.

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Co-authorship regarded publication included in Elena Parmiggiani's PhD thesis

(cf. the PhD regulations § 10.1, section 5 and the dr.philos regulations § 3, section 5, http://www.ntnu.edu/ime/research/phd/forms).

Candidate's described contribution to:

Parmiggiani, Elena; Hepsø, Vidar. (2013) ***Pragmatic Information Management for Environmental Monitoring in Oil and Gas.***
In Proceedings of the 21st European Conference on Information Systems (ECIS), 2013, Utrecht, The Netherlands, June 5-8, 2013, paper 65.

Parmiggiani had the main idea as a result of the conversation with Vidar Hepsø. Parmiggiani wrote the paper and Hepsø contributed through discussions, extensive comments, and corrections of the paper.

Statement by the co-author:
I hereby confirm that the doctoral candidate's contribution to this paper is correctly identified above, and I consent to Elena Parmiggiani including it in her PhD dissertation.

Trondheim, 12.02.2015

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Candidate's described contribution to:

**Parmiggiani, Elena, and Marius Mikalsen. 2013. "The Facets of Sociomateriality: A Systematic Mapping of Emerging Concepts and Definitions."
In *Nordic Contributions in IS Research*, edited by Margunn Aanestad and Tone Bratteteig, 87–103. Lecture Notes in Business Information Processing. Springer Berlin Heidelberg.**

Parmiggiani and Mikalsen had the idea of conducting the literature review. The literature search was split among the two authors. Parmiggiani conducted most of the literature analysis and wrote sections 3, 4, and 5. Mikalsen contributed by writing sections 1 and 2 and through discussions and corrections.

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<u>*Candidate's described contribution to:*</u>

Mikalsen, Marius; Parmiggiani, Elena; Hepsø, Vidar. 2014. "Sociomaterial Capabilities in Integrated Oil and Gas Operations - Implications for Design."
In Proceedings of the European Conference on Information Systems (ECIS) 2014, Tel Aviv, Israel, June 9-11, 2014, track 20, paper 3.

Mikalsen had the main idea for this paper as a consequence of the collaboration between us. Empirical data were made equally available by Parmiggiani and Mikalsen. Parmiggiani participated to the analysis and wrote the majority of section 2 and 3.1. Parmiggiani also wrote parts of section 4. Other sections were written by Mikalsen. Parmiggiani proposed the elaboration of the concept of convergence, whereas Mikalsen that of maintenance. Parmiggiani also contributed to the discussions with Mikalsen and Hepsø. Hepsø contributed to the elaboration of the empirical data and input to the context. Hepsø also provided feedback and corrections.

<u>*Statement by the co-author:*</u>
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Candidate's described contribution to:

Parmiggiani, Elena; Monteiro, Eric; Hepsø, Vidar. (2014) ***The Digital Coral: Infrastructuring Environmental Monitoring.***
Submitted to Computer Supported Cooperative Work (CSCW) (second round of review)

Parmiggiani had the main idea for the paper and proposed to elaborate the notion of infrastructuring through bootstrapping and enactment. Monteiro had the idea of submitting the paper to a CSCW outlet. Parmiggiani was the main responsible for the data collection and the data analysis which was aided by the frequent discussions with Monteiro and Hepsø. Parmiggiani wrote most of the paper, Monteiro wrote the majority of sections 1 and 2 and polished and corrected the article. Hepsø contributed also by providing corrections, feedback, and by writing subsections in earlier versions of the manuscript.

Statement by the co-author:
I hereby confirm that the doctoral candidate's contribution to this paper is correctly identified above, and I consent to Elena Parmiggiani including it in her PhD dissertation.

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Candidate's described contribution to:

Parmiggiani, Elena; Monteiro, Eric (2014) ***The Nested Materiality of Environmental Monitoring.***
Submitted to the Scandinavian Journal of Information Systems (under review after second round revision)

Parmiggiani had the main idea for the first version of the paper as a result of the frequent discussions with Monteiro. The initial version however changed as part of the revision process and the current version is based on an idea by Monteiro.
Parmiggiani wrote most of the paper and Monteiro wrote sections 1 and 2 and provided feedback. He also corrected and polished the paper. Parmiggiani was the main responsible for the data collection; data analysis was mostly conducted jointly between the two authors.

Statement by the co-author:
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Candidate's described contribution to:

Parmiggiani, Elena; Monteiro, Eric (2014) ***A Measure of 'Environmental Happiness': Infrastructuring Environmental Risk in Offshore Oil and Gas Operations.***
Submitted to Science & Technology Studies.

Parmiggiani had the main idea for the paper and wrote most of it. Monteiro wrote section 7 and contributed in structuring the paper. He also participated in discussions and provided corrections and feedback. Parmiggiani was also the main responsible for the data collection and analysis.

Statement by the co-author:
I hereby confirm that the doctoral candidate's contribution to this paper is correctly identified above, and I consent to Elena Parmiggiani including it in her PhD dissertation.

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Candidate's described contribution to:

Parmiggiani, Elena; Monteiro, Eric (2015) ***Environmental Sustainability: Implications for Green IS.***
Submitted to Management of Information Systems Quarterly.

The idea for looking into the Green IS field is the result of the frequent discussions between the two authors. Parmiggiani conducted the systematic literature review and wrote most of the paper. Monteiro wrote section 1 and participated through extensive discussions and feedback, in particular on the structure and of sections 3, 5 and 6. Parmiggiani was the main responsible for the data collection and analysis.

Statement by the co-author:
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