6 KNOWING

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> One must therefore know the *method of knowing* in order to grasp the *object to be known*.
> —Bachelard (1949/1998, cited in Rheinberger 2005)

The empirical focus of this chapter is on sand. With many of the hydrocarbons on the Norwegian continental shelf trapped in Jurassic sandstone, the risk of sand in the production flow is immanent. Entering the production system through wells drilled thousands of meters into the earth's crust, the fluid rushing into the well sweeps sand with it along the pipelines all the way to the topside processing plant, where sand settles in the tanks that separate crude oil and natural gas from the other constituents of the fluids. Sand deposits threaten to reduce the plant's processing capacity and oil quality. More importantly, however, sand particles rushing at high speeds through the pipelines erode the piping, eating away at the valves controlling the fluid flow as well as the valve casings. Left unchecked, high-speed fluids, gases, and sand particles jetting out of a puncture may cause catastrophic environmental damage as oil gushes into the ocean, while leaking gas carries a danger of igniting and exploding on the topside platform.[1] It is therefore important for the offshore control room operators to take mitigating measures to prevent sand from entering the production system.

Sand-monitoring rounds are traditionally part of the offshore roughnecks' daily inspections at the offshore processing plant. When roughnecks discover sand in the production equipment, offshore laboratory assistants embark on a regime of inspecting and emptying the sand traps—cups mounted underneath each flow line where the heavier sand particles settle as fluids rush past—to locate the originating well. It takes time for sand deposits to accumulate in the sand traps, though, so laboratory assistants can only inspect the cups once during every eight-hour shift. It may take days or even weeks before the well is back in production without new sand entering it.

Sand-monitoring routines were targeted or digitalization for reasons of efficiency, quality, and safety. The manual routines are labor-intensive, error prone, and time-consuming. Responding to business pressure, oil operators on the Norwegian continental shelf, including but not limited to NorthOil, are continuously engaged in cost cutting. An important, and for sand-monitoring routines relevant, result of this is to shift work (and workers) from offshore to onshore. Offshore workers on the Norwegian continental shelf have negotiated a two-weeks-on, four-weeks-off work schedule in addition to offshore salary bonuses. With most if not all offshore workers globally working two weeks on, two off, oil operators are constantly looking for ways to shift tasks onshore or automate them altogether through digitalization. As pointed out in chapter 1, removing manual tasks and workers from offshore installations has a long, ongoing history despite warnings about eroding safety from labor unions and the Petroleum Safety Authority Norway (see also Ryggvik 2018).

In the context of this book, the case of digitalizing sand-monitoring routines is illuminating. It ties directly into the fundamental discussion raised in chapter 1 about the conditions under which the representational capacity of digital data holds organizational consequences (Kallinikos 2007). Through a series of efforts, NorthOil explored how different digital representations—Internet of Things (IoT)–based sensor measurements, graphs, plots of historic data, and predictive simulation models—attempted to stand in for the all-too-physical reality of sand eroding the pipes, chokes, and valves of the oil production facility (Leonardi 2012).

A sequence of digital renderings of sand was successively superimposed onto physical sand, traditionally collected in cups and analyzed in laboratories. What, then, in the everyday practices of sand monitoring is "sand"? Closer to the heart of this book, what role do the different digital renderings of sand play in the transformation of knowledge-based practices of sand monitoring? In other words, I am focused more on the (epistemological) concern of how sand monitoring is achieved than the (ontological) concerns about what sand really is. When digitally transforming work practices rely on a multitude of connotations of sand, be it physical detected sand deposits in sand traps, sensor readings, or historic and projected plots, how do operators know and act upon sand? How do operators know—enough—about sand to take mitigating actions, such as ordering maintenance interventions, implementing supplementary inspections, or, ultimately, reducing production capacity?

Anything but reified, knowing underpins action/practice (Alavi and Leidner 2001). Knowing, Orlikowski (2002) notes, is "a situated knowing constituted by a person acting in a particular setting and engaging aspects of the self, the body, and the physical and social worlds" (252). However, as influential insights in the social sciences have made clear during the last couple of decades, all knowing practices are material (Barad 2003; Cecez-Kecmanovic et al. 2014; Latour 1999; Orlikowski and Scott 2008). There is thus a broad consensus *that* knowing is material but a significant divergence regarding *how*, be it "entangled" (Orlikowski 2006), "imbricated" (Leonardi 2013), or "inscribed" (Monteiro and Hanseth 1996). The challenge is to specify, in interesting detail, how the knowing of digital sand is done—that is, unpack the underpinning empirical conditions and mechanisms.

The versatility of digital technologies relies on the capacity to digitally represent and subsequently algorithmically manipulate selected physical processes, objects, or qualities within a domain (see, e.g., the key role of sensors and IoT pointed out in chapter 1). How closely the digital representations mimic the physical domain varies from directly mirroring, to resembling, to decoupled. Pressing the capacity of digital representations to decouple as much as possible is important because this "has the greatest potential to change work's historically tight coupling to the physical and, with it, the work relations of people to objects and each other" (Bailey et al. 2012, 1486). In other words, the disruptive potential of digital technologies assumes the capacity of digital representations to decouple from, not merely mirror, existing work practices (Borgmann 1999).

Several decades of empirical studies of digital technologies in organizations, however, demonstrate how technological potential often fails to translate into organizational change in practice (Zuboff 1988; Leonardi 2012). For digital representations to underpin organizational change in practice, they need to be implicated in consequential decisions and actions within work practices. To become *organizationally real*, digital representations, beyond their mere potential/capacity for decoupling, need to be incorporated into organizational practices; digital representations are not, but may become, organizationally real. This entails that the focus is on the conditions and mechanisms through which digital representations get woven into institutionalized work practices of sand monitoring.

Thus, the empirical case of successive stages of digital sand presented below is not one of disruptive change. On the contrary, it is an account of the gradual institutionalization of digital representations, increasingly distant from "real" sand, into work practices. A crucial aspect of the case is the manner in which a singular digital representation, in and of itself, carries little weight; to carry more weight, it needs to be tied into a broader set of supporting digital representations, a *machinery*.

THEORETICAL FRAMING: AUTOMATION AND IOT-ENABLED VISIONS OF INDUSTRY 4.0

Visions and proclamations of the Second Machine Age, or Industry 4.0, or the Industrial IoT draw heavily on rich yet underspecified accounts of what digitalization is and entails. Enabling technologies such as cloud computing, big data/analytics, robotics, and the IoT are regularly identified but without adequate explanation as to where, when, and how digitalization unfolds.

Historically, digitalization has been tied to automation, the substitution of previously manual tasks for digitalized ones.[2] The introduction of computers in the workplace in the 1970s, 1980s, and part of the 1990s regularly spawned fears of job loss and deskilling among employees (Braverman 1974; Friedman 1977). In Europe, more than the US, unions mobilized to respond to these perceived threats. In some countries, this resulted in new legislation and regulations ensuring employees' right to consultation or participation when computers are introduced in organizations (Asaro 2000; Muller and Kuhn 1993).

Conceptualized as computerization, the introduction of digital technologies was historically tied to their potential to automate a wide set of work tasks (Friedman and Cornford 1989). Braverman (1974) argued in an influential study that the scope of computerization would imply widespread deskilling of work tasks. The defining assumption, automation by substituting for manual work tasks, met with growing critique of both an empirical and theoretical nature.

Empirically, scholars demonstrated that the results of computerization were significantly more varied than what Braverman maintained. Barley (1986), for instance, showed how the introduction of similar computed tomography scanners in different hospitals led to different work routines and roles for radiologists. Similarly, the coining of the so-called productivity paradox underscored the variations in outcomes of computerization: studies found negative, zero, and positive correlation between investments in computers and productivity (Kling 1996). A series of studies on computerization demonstrated that digital technologies involved local appropriation and hence were not merely automation (see, for instance, DeSanctis and Poole 1994).

Theoretically, the variance in empirical results of computerization led to identifying an assumption of technological determinism in Braverman. It was, accordingly, necessary to establish the significance of digital technologies as something different from (only) automation i.e., that the dynamics around the development, use and subsequent spread of digital technologies differ from those predominately addressing automation. So how and why, then, are digital technologies different?

In Zuboff's (1988) formulation, digital technologies' potential for transformation was unique as, beyond automation, they had the ability to informate (see discussion in chapter 1). Informating relies on a "spillover" effect in digital technologies—that is, data input to processes and tasks is not consumed. The fundamental insight of Zuboff's notion of informating was to underscore the inherently open-ended, unfinished, and extendable character of digital technologies. This has been incorporated into more recent conceptualizations of digitalization (see Garud et al. 2008; Kallinikos et al. 2013) as digital technologies are inherently dynamic and malleable (Yoo et al. 2010).

Scholars of digitalization, albeit from different angles and with different formulations, provide strikingly similar insights: Yoo et al. (2010) identify the defining quality of digital technologies, their (algorithmic) programmability and layering; Zittrain (2006) characterizes the open-ended extendibility of digital technology via the notion of "generative"; Lusch and Nambisan (2015, 160) identify the defining ability of "liquefaction" of digital representation decoupled "from its physical device or form" (see chapter 1); and Borgmann (1999) notes the ability of digital representations to "illuminate, transform, or displace reality . . . [and hence] disclose what is distant in space and remote in time" (1).

Thus, to talk of tools and technologies mediating the outside world downplays to a level of nonexistence the active contribution of the tool/technology. Breaking away from a representational perspective where reality is passively mediated by tools and technologies (Pickering 2010; Jones 2019), a performative perspective underscores their coconstitutive relationship (MacKenzie 2006). In a widely cited study of the financial option market, MacKenzie and Millo (2003) explicitly set out to demonstrate the performativity of 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 (2003, 107) 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" (cited in Orlikowski and Scott 2008, 461). The crucial relevance for the argument in this book is that knowing sand is inherently caught up in the sociomaterial means of knowing sand; *what* operators know about sand is *how* they know it (Rheinberger 2005).

The above outlined theoretical interest in characterizing digitalization is radically boosted by the empirical emergence of big data together with data-driven, machine learning–based forms of algorithmic manipulation. Socially informed critical studies of digitalization, to further our understanding, need to combine a theoretical grasp of digitalization with an empirical grounding in organizational dynamics, a combination largely missing when it comes to the data-driven algorithmic approaches literature reviews consistently find (Günther et al. 2017; Sivarajah et al. 2017). A particularly helpful approach is provided by Bailey et al. (2012). They analyze the *degree* to which digital representations are disembedded from their referent. This paves the way for inquiries, like the present one, about the conditions under which (degrees of) disembedded digital representations carry weight. Drawing on the semiotics of Peirce, Bailey et al. identify three configurations of the digital representation/physical referent relationship: (1) indices, where digital representations are but labels for their physical referents, the desktop metaphor of graphic interfaces being an example; (2) icons, where the digital representations are similar but not the same—for example, a videoconference instead of a face-to-face meeting; (3) symbols, where the digital representations bear no resemblance to the physical referent, and the link is solely based on conventions.[3]

Taking the digitalization qua liquefaction to its limits, some studies focus on simulation as explorative—a radical break from existing work routines. For instance, Dodgson et al. (2013) analyze how simulations are used in a business organization to promote "processes that induce and sustain the craziness of wild ideas" (1359; see also Dodgson et al. (2007), exploring radical design changes). As pointed out above, pursuing the potential of digitalization, in principle, as completely disembedded from the referent sidesteps the crucial concern of how, in practice, to give simulations organizational weight. The latter inevitably involves focusing on the relationship of digital representations to their referents.

One stream of work focuses on the dangers of simulations replacing their referents. Turkle's (2009) work emphasizes the dangers of simulation-based renditions of reality given their strong, seductive capabilities. As users are gradually immersed in simulations, "Familiarity with the behaviour of [digital representations] can grow into something akin to trusting them, a new kind of witnessing" (Turkle 2009, 63). The physical referents are central to Turkle's analysis of simulations to the extent that she warns of the dangers of their disappearance.

Leonardi's (2012) work on the automotive industry's attempt to replace physical (and costly) car crashes in safety design models with simulated crashes is one of the few longitudinal studies of simulations in organizations. A principal finding is that simulations, to carry organizational weight, need to be icons rather than symbols. As Bailey et al. (2012), drawing on Leonardi's study, point out, "This tight coupling in simulation means that people who create representations are highly dependent on physical referents" (1500). Phrased in Peirce's vocabulary, Leonardi (2012) argues how simulations can avoid being empty representations (symbols) and gain organizational relevance by becoming icons—that is, enjoy immediate recognition through their "similarity with the [physical] object" as "seeing is believing" (14–16).

Consistent with insights from infrastructure studies, however, singular digital representations of sand carry little weight. To carry weight, knowledge about sand needs an accompanying infrastructure of vocabularies, institutions, practices, and technologies (Poovey 1998; Porter 1996). With science and technology studies (STS) underscoring the local, embodied, and enacted nature of knowing "facts," the ability of knowing sand to "travel" from the offshore installation to the onshore operations center may seem a paradox: "If, as empirical research securely establishes, science is a local product, how does it travel with what seems to be unique efficiency?" (Shapin 1995, 307). In the colorful phrasing of Morgan (2010), the apparent paradox is resolved as knowing sand and "facts require[s] a variety of charismatic companions and good authorities to travel well" as "we depend upon systems, conventions, authorities and all sorts of good companions to get facts to travel well—in various senses—and danger may lurk when these are subverted or fail to work" because "once facts leave home, it is more difficult to keep them safe" (4–6). As will be demonstrated empirically below, facts and knowledge about sand, expressed in a variety of digital representations of sand, also need traveling companions to carry organizational weight in NorthOil.

THE CASE OF SAND-MONITORING ROUTINES: THE SUPERIMPOSING OF DIGITAL REPRESENTATIONS

The setting for the case below on successive stages of digitalizing sand monitoring—digital sand—is the onshore operation center for daily production and its interactions with the offshore control room at the field in question on the Norwegian continental shelf. In parallel, corporate research and development (R&D) engineers in close collaboration with technology vendors, producers of sensors, and a standardization organization are engaged in a digitalization effort to improve (in terms of quality, efficiency, and safety) sand monitoring in which they, in addition to field testing, organize workshops and meetings to discuss and explore alternative approaches to digital sand.

As such, the case was an early attempt at what is now a proliferation of remotely operated onshore control centers being delegated increasingly more tasks and responsibilities (see Latour [1987]'s notion of centers of calculation). Remotely operated control centers come in different and evolving configurations (Hepsø and Monteiro 2021). Some, like the sand-monitoring case below, set up corporate control rooms that are assigned a particular field with associated "satellites" (additional, neighboring fields tied into the same processing and transportation infrastructure as the original ones, thus benefiting from the sunk investment). Others act as expert or consultation centers serving a group of oil fields. Yet others are run from the premises of the service provider, not the oil operator. In sum, this has resulted in the currently established dominant operational model of offshore installations being minimally manned or unmanned. Configurations of remotely operated control centers are thus vital ways in which offshore oil on the Norwegian continental shelf is pushing toward visions of automated oil production.

In what follows, a longitudinal account of the digital transformation of sand monitoring over a period of almost twenty years, from the mid-1990s to 2012, is presented. It sheds light on how, if at all, digital representations become organizationally real. Through a succession of different initiatives in response to setbacks and challenges, digital representations of sand are successively superimposed onto physical sand; gradually, digital sand becomes organizationally real.

The transformation of sand-monitoring practices is traced through four periods during which configurations of material arrangements (typically sensors but also the physical equipment associated with leading fluids from the wells) and digital algorithms (for transforming sensor output into different digital data) successively disembed physical sand (the referent) into digital representations (the reference; see table 6.1). With the successive

Table 6.1
An overview of the different periods of digital sand monitoring.

Period	Focus	Key technologies	Central actors
Period 1 (early 1990s): organizational consequences of false alarms	Testing of sand-monitoring measuring devices (sensors). Struggling with proliferation of false alarms that underpin confidence hence relevance of the sensors.	Singular, stand-alone sensors (electrical resistance). No algorithmic transformation beyond monitoring threshold values.	Offshore control room operators and onshore production engineers. Dialogue with vendor of sensors to increase accuracy.
Period 2 (mid-1990s–early 2000s): meshing sand monitoring with related routines	Real-time measurement of sand content as characteristic of the well flow to replace manual and time-consuming sand-monitoring practices. Operational principle of zero sand tolerance implemented as immediate shut-in of sanding well.	Digital sand sensors (acoustic, electrical resistance). Algorithms transforming acoustic/electrical resistance data into measure of sand content in well flow. Simple user interface to sensor measurements.	Digital sand mitigation within offshore control room operators' production control practices for minimizing disruptions to offshore processing plant. Onshore production engineers supported control room operators in investigating sand alarms.
Period 3 (early–mid-2000s): sand, an interactive, algorithmic phenomenon	Combining real-time measurements with geomechanical theory and with geomechanical knowledge on causes of sand influx transforms digital sand from a characteristic of well flow to an indicator of events in the reservoir. Zero sand tolerance policy implemented by sand mitigation strategies fitted with the kinds of sand events causing sand influx.	Visualizations of sand content data development over time in trends. Inclusion of data points from other sensors (temperature, pressure) to better identify false alarms. Dashboard aggregating alarms across all wells on the oil field.	Sand mitigation nominally within offshore control room operators' production control practices. Sand mitigation handled in practice by onshore production engineers to limit the impact of sand incidents on optimizing daily production volumes.
Period 4 (mid-2000s and onward): sand as a machine learning–based predictive model	From zero sand tolerance policy toward predicting the effect of producing with limited amounts of sand in the well flow.	Algorithm for predicting erosion on pipeline bends and valves.	Sand monitoring exclusively in the domain of optimizing daily production volumes by coordinating erosion of production equipment with maintenance shutdowns of the offshore plant.

disembedding of physical sand throughout these four periods, the referent/reference relation expands the scope of digital representations from a real-time measurement of sand influx in individual wells to simulations of sand erosion in the production equipment. The character and focus of sand-monitoring practices transform with the different renderings of digital sand.

PERIOD 1 (EARLY 1990S): ORGANIZATIONAL CONSEQUENCES OF FALSE ALARMS

“So, you may have sand in the production system,” explains NorthOil’s leading expert on sand mitigation technologies. He is giving a presentation at one of the many workshops of the joint industrial R&D project. The undersized meeting room is stiflingly hot, with between ten and fifteen people in attendance cramped around a too-small conference table. Still, representatives from most of the major operators and leading digital sensor technology vendors in the North Sea region are present. During this presentation, the sand expert—fondly referred to as Mr. Sandman within the national petroleum industry—reflects on some of the corporation’s earliest experiences with introducing a digital sand-monitoring system for use by offshore control room operators in the mid-1990s.

“And these are the [sand] data values,” he continues as he draws a jagged, rising line with a black marker in a coordinate system on the whiteboard. Still with his back turned to the rest of us attending his presentation, he picks up the red marker. “And then there is this one single peak above the alarm limit,” he says as he draws a horizontal red line across the coordinate system to indicate the alarm level, “and then you have triggered an alarm in the offshore control room’s process control system. That’s just stupid!” He turns toward the rest of us, pausing to emphasize his point.

Some workshop participants nod in agreement. Others murmur, possibly in consent, or maybe just to indicate they are paying attention.

After a pregnant pause, the sand expert continues: “What happened, you see, was that they [the offshore control room operators] ignored the alarms, and they said”—and now he speaks with a theatrically exasperated voice, paraphrasing the control room operators—“‘The system you have is rubbish [and] we are not able to monitor for sand influx.' So, they turned it off, never to use it again."

What the sand mitigation expert is vividly demonstrating is the organizational consequences of false alarms. The offshore control room is a hectic place. The two operators working there have to be vigilant at all times to make quick decisions in response to audio alarms going off when key operating parameters exceed preset alarm limits—and alarms go off on a regular basis. If you have sand sensors with "one single peak" triggering a full control room alarm, it is disruptive to daily control room operations. Sensors, sand sensors included, are notoriously error prone and therefore regularly produce outliers that the operators have to ignore. To be of practical use, sand-monitoring systems need to be less brittle, less sensitive to noise, and hence more robust. Failing in this regard, the result was that the complete sand-monitoring system was turned off. These early experiences with sand sensors provide important empirical elaborations on the capacity of liquefaction discussed in chapter 1—that is, the disembedding of the sand sensor measurements from the physical presence of sand in the production flow. Despite a capacity, it is not realized organizationally; it never becomes organizationally real.

The petrochemical-processing plant is a controlled system, very much akin to a laboratory, being designed as a closed-loop system. The term "closed-loop system" stems from cybernetic theory, which describes it as a controlled system that deterministically transforms input to output. As a closed-loop system, the petrochemical-processing plant is physically constructed as a series of subsystems with fluids streaming through and with each subsystem in itself a closed-loop system. Physical barriers prevent possible instabilities and fluctuations within one subsystem from spreading throughout the entire processing plant. Dampening fluctuations this way, the physical setup creates a deterministic system. When an operating variable such as pressure increases or decreases at a point in the petrochemical-processing plant, it does so linearly. All the control room operator needs to see is that the figure increases or decreases. In this laboratory-like environment, there are no intervening variables interfering with measurements.

The well flow, in contrast, is by no means as well behaved. For the sand sensor in question, the vendor had tested and verified the digital sand-monitoring system under laboratory conditions. Hence, the sand data help in the sense of yielding adequately accurate laboratory results. The vendor in dialogue with the technical division of NorthOil agreed that these tests fulfilled the requirements set by NorthOil. When mounted within pipelines embedded deep within the earth's crust, however, multiple factors registered as increasing sand content. Furthermore, unlike the processing plant the rocks and fluids within the reservoir were by no means under cybernetic control. Developments within the reservoir therefore did not register as linear or deterministic changes in the sand data. Despite being subjected to rigorous testing and technical qualifications, the credibility of digital sand for this sand sensor failed to hold up in production settings beyond laboratory conditions.

The offshore control room operators could not live with the resulting level of false alarms. Their primary concern is to ensure stable, uninterrupted operations of the topside processing plant. The rationale for introducing the digital sand-monitoring system was to reduce production loss due to sand mitigation. For the control room operators, though, reduced production volumes were of limited concern; their concern was and remains stable operations of the offshore production plant. Compared with the deposits of reeking, viscous, tarry sand accumulating in the topside production equipment, sand alarms turned out to be mostly false. In the time-pressured setting of the control room, the operators simply had no time to investigate whether triggered sand alarms were false or not.

PERIOD 2 (MID-1990S TO EARLY 2000S): MESHING SAND MONITORING WITH RELATED ROUTINES

Despite this setback, NorthOil pushed forward with its effort to introduce digital sand monitoring in the production organization. A few years later, the digital sand-monitoring system was in full use. By that time, however, the system had undergone several revisions. In addition, circumstances had changed in important ways. With a growing number of aging oil fields in the North Sea during the early 1990s, NorthOil—along with other operators in the region—was experiencing an increasing frequency in production disruptions because of sand in the production system. Ineffective manual routines for detecting sand entering the production system were identified as a principal contributor to significantly reduced production volumes. Thus, the prospect of an IoT-based, real-time rendering of digital sand, making it possible to identify and intervene immediately to stop the influx of sand, appeared increasingly attractive from a business perspective.

With renewed urgency, NorthOil mobilized many of the specialist communities previously involved in developing the original version of the sand-monitoring system to discuss how the data produced by digital sand sensors could be institutionalized into everyday practices, not become yet another technological pilot that gets abandoned soon after leaving the sheltered environment of the laboratory. As a result, digital sand monitoring was woven into the larger sociomaterial network of the offshore/onshore production organization to generate new data streams with associated arrangements for producing and handling these data streams, actualizing onshore production engineers' existing knowledge work in new ways to make real-time sand data actionable. This work spanned many settings and different regimes for making digital representations of sand robust.

In developing the digital sand-monitoring system implemented in the offshore control room, first these specialist communities focused on ensuring a "faithful" (see chapter 1) robust one-to-one reference/referent relationship between sand and its digital representation. Several research communities and vendor companies explored various possible technologies for doing this. With IoT-based sensing expanding in domains other than sand monitoring, they also considered repurposing existing sensors. The lead software engineer with the major vendor of digital sand-monitoring systems recalled: "We already had technology for inspecting pipeline integrity. When we saw the tender for a digital sand-monitoring system, we asked ourselves if our existing technology could also be used to detect sand in the well flow."

Measuring sand content required not only the development of digital sensor technologies but also the development of a standardized measuring scale. An international standardization organization had been tasked with developing a representative and reliable scale for the measurement of sand content, a standard that was missing. Standardizing sand content measurements, however, proved cumbersome. The problem, as O'Connell (1993) points out, was to find a *method* of measuring that was not (too) sensitive to the circumstances of its application. In the case of sand sensors, two different types of probes (i.e., sensors) were designed and tested, each tied to a different method of measuring sand. One was acoustic. It was based on picking up the acoustics of grains of sand hitting a surface and emitting a sound. The other was based on principles of electrical resistance. It was based on Ohm's law and measured changes in electrical resistance across a series of metal probes. Sand erodes the metal probes, causing a change in electrical resistance. This is transformed into a measure of sand content.

The problem facing both the proposed sand sensors, however, was their sensitivity to other phenomena or aspects of the environment than the intended one, sand. For instance, as a result of being designed around a hypersensitive microphone, the acoustic sand sensor registered all sound changes in the well flow, including the din of the production machinery traveling throughout the pipeline system. Likewise, changes in well flow temperature induce changes similar to those of erosion in resistance and will register as sand even if no sand is in the well flow. A senior engineer with the standardization organization summarized the situation during a project workshop:

> The specific way of measuring sand depends on a number of factors. For instance, different approaches are influenced by different factors such as pressure. We tried several approaches, but in the end, we arrived at the simplest way of measuring sand content: that of grains of sand flowing across a sensing probe every second.

The focus of these efforts was, again, on developing a credible measurement understood in terms of a faithful digital rendering of sand. Through testing and experimentation in their laboratory setting, the standardization organization's research engineers struggled to maintain the faithfulness of the measurement under differing conditions. In the end, settling on measuring sand content as the number of grains flowing across a point in space per second is the product of the research engineers prodding and tweaking the material arrangements to find the most robust relationship between sandy fluids streaming into a well and sand influx as measurable characteristics of the well flow.

During this, not only *what* constituted sand (a sensor measurement, not the tactile manifestation of accumulated deposits of a reeking, black, viscous tarry mass in the processing equipment and sand traps) and *how* it was detected (measuring the number of grains of sand flowing per second, not taking samples with subsequent laboratory testing) but also *who* was doing sand monitoring changed. Instead of offshore roughnecks, the task was shifted to onshore operations centers.

With the delocalization of digital sand, onshore production engineers and their professional expertise were mobilized to help monitor and mitigate sand. Production engineers' pragmatic concern is to optimize the field's daily production volumes. Their daily tasks evolve around planning and prioritizing production to optimally utilize the offshore production plants' processing capacities. They, much like the explorationists described in chapters 4 and 5, draw upon intimate knowledge of individual wells: the particulars of their designs, their production history, and their idiosyncrasies. "If you only learn one thing from your stay here," a production engineer explained during the lunch break one day, "[it is that] a well is never simply a well." What he meant, he elaborated, is that a well is "only a word." All wells are "different beasts," and "it's our job to know all of them."

This specialized and intimate knowledge of the material basis of daily production became increasingly central when investigating the fluid relation between digital symbols and their references from the mid-1990s onward. Digital sand management was integrated with production engineers' daily work tasks within NorthOil's onshore production organization. Working primarily with planning activities, the production engineers had more time to investigate digital data and their credibility. Digital sand monitoring latched on to these developments as production engineers would draw upon their existing knowledge of wells and sensors to triangulate sensor data with other information to determine whether a sand alarm was really caused by sand in the well flow or some other factor. "I'm not entirely convinced this is sand," one of the production engineers commented after the control room had informed him of a sand alarm. "The [sand] probe in E-37 has been acting up ever since the well was offline for maintenance." Hence, the necessary organizational credibility of sand sensors was *crafted* through the production engineers' efforts to control the data quality and calibrate and triangulate sand sensor measurements. To support this new form of sand-monitoring practice with increased roles and significance for the production engineers, the vendor of the sensor changed the entire sensor design by adding an additional probe shielded from sand to generate a data stream immune to the effects of sand but sensitive to other factors that could register as sand. Such interferences may include changes in the well flow itself, such as temperature and flow rate, or may be generated by the sensor itself, either because it has been mounted incorrectly, is broken, or is starting to wear out. The sand-monitoring system's vendor prototyped a new sand-monitoring application, correlating sand measurements with influencing factors so the production engineers could sort out data interferences. Upon noting a sand alarm, the production engineers use this application to weed out intervening factors registering as sand.

The production engineers are also part of the extended network of professions and activities working tightly to maintain and operate the production facilities. The production engineers draw upon the output of many of these activities, along with their own intimate knowledge of individual wells and how they may affect adjacent wells, to prod and investigate the relationship between digital sand data and sand entering the wells. Another sand sensor vendor then used this information to develop an elaborate calibration procedure that the production organization integrated with existing testing procedures. This is what NorthOil's leading expert on sand mitigation technologies was discussing in his presentation of the company's earliest experiences with digital sand monitoring, described above, during period 1. Having gained the attendants' attention with his statement about the control room operators turning off the digital sand-monitoring system, "never to use it again," he explained: "As part of velocity testing of the well, we would inject a pre-determined amount of sand grains into the well flow and then measure the signal at different production rates to calibrate the sand sensor." Thus, by linking sand monitoring with other routines, in this case well testing, the sand sensor received their much-needed calibration to enhance their organizational credibility. Another part of the maintenance organization developed new routines for ensuring that the sensors are mounted correctly, and the vendor made minor modifications to the sensor design to make them harder to mount incorrectly. At the same time, the production engineers started keeping tabs on the state of individual sand sensors in a collection of different documents and spreadsheets. Consequently, the nature of the work of monitoring and mitigating sand in the production system, as well as the organizing of this work, transformed with the digitization of sand.

While the production engineers' sand-monitoring work came to be increasingly centered around digital representations, a notable feature of this transformation of sand monitoring was an accumulation of representations, both digital and physical. These representations are always all in play, as production engineers also draw upon the topside inspection procedures to verify whether there is sand in the well flow. When monitoring for sand, there is never a dichotomous separation of the physical and digital. Rather, the production engineers move seamlessly between the two, as illustrated by the following episode.

Matt, that day's on-call production engineer, received a phone call from the offshore control room. “We have sand deposits in the separator [part of the offshore production system],” the control room operator said. Matt seemed puzzled. Looking at the dashboard showing the status of recent sand alarms across the field, he said, “There have been no sand alarms.” “But we *have* sand in the separator,” the control room operator insisted. Matt cycled through screens in the sand-monitoring application, looking for possible indications of sand but finding none. Leaning across the table toward a set of sand samples the production engineers kept handy, Matt picked one up. The vial's label said “Silt.” Holding it by its neck, Matt shook the vial, looking at the quality of the sand swirling within. “What kind of sand is it that you've found?” he asked. “Silt,” stated the control room operator. “Ah,” Matt said, sounding relieved: “Silt is too fine to register on our sand sensors. There's no erosion danger, but let me know when you've located the sanding well [i.e., the one among the field's many that is producing silt] so we can take [mitigating] measures.” The control room operator confirmed, “I'll set the lab assistants on it at once” and ended the call.

During this period, digital sand as a characteristic of the well flow became naturalized, and digital sand monitoring institutionalized, as a routine. As the routines and techniques investigating the organizational credibility of digital sand stabilized, however, NorthOil pushed further to improve how it used the digital sand-monitoring system to optimize daily production volumes, as explained below.

PERIOD 3 (EARLY TO MID-2000S): SAND, AN INTERACTIVE, ALGORITHMIC PHENOMENON

"So, look here, and see that we have a steep increase in the measured amount of sand flowing across this probe," Vinnie,[4] one of the onshore production engineers, said. Vinnie had been the on-call production engineer the night before, and the offshore control room operators had called him to investigate a sand alarm in one of the field's many wells. At the heart of Vinnie's retelling of the incident was a graph with plotted sand data in a time line. The first thing he had done upon receiving the phone call was to open the application that plots this graph. "I'm quite certain we have sand entering the well," he continued, "but then I look at the down-hole pressure here." He pointed to a green trend line plotted in the same coordinate system. "I realize that almost no fluids are streaming through the well. I would normally ask the control room operators to choke down [reduce the flow rate of the well] to prevent sand from damaging the production equipment. In this case, however, I am asking them to choke up. We are dangerously close to a shut-in pressure where sand will simply flow back down the pipeline."

Innocuous as this statement might have seemed, it bears witness to a significant shift in how NorthOil mitigates sand in the production system. The operational procedures for mitigating sand in the well fluids remained largely unchanged after introducing the digital sand-monitoring system in the onshore production organization in period 2 outlined above. There was a relatively clear and stable division of labor between off- and onshore tasks pertaining to sand management. The onshore production engineers were mainly used to confirm whether or not the sand alarm actually indicated sand. Once the onshore production engineers confirmed there was indeed sand in the well flow, the offshore control room operators would reduce the production rate from the well in question to limit fluid drag within the reservoir and, hopefully, the amount of sand swept along with the fluids being drained out of it. The problem is that with copious amounts of sand in the fluids, a loss of well flow velocity causes the sand to flow back and fill up the pipelines. But as NorthOil's leading expert on sand mitigation observed:

> Looking back at the data collected by the sand sensor system, the data was clear for those of us with knowledge of how sand producing wells behave. The production engineers at the operations center lacked this knowledge. They did not recognize the indicators before the pipeline was filled with sand and irreparable damage had been done.

The sand-monitoring software Vinnie was using came about as NorthOil initiated a large research project to improve operational communities' ability to handle sand incidents. Instead of representing sand as an absolute number that changes with each sand measurement, the digital sand system vendor made use of plotting sand data in a time series graph, as one software engineer with the vendor explained:

> The information was presented [in the user interface] in a way they could not relate to. It [the information] was just [presented as] a number, but what does that number mean? They needed to see trends and be aware of the system's limitations. They needed to consider factors that affected the measurements, but which were not sand related. So, if they had an alarm, they had to manually assess whether the alarm was an actual incident.

What appears to be a simple engineering trick for the vendor's lead software engineer, however, opened a window of opportunity for improved mitigation strategies. Sand in the production system has been a well-known problem within the international petroleum industry since the 1940s. By the 1970s, researchers within the earth sciences had formulated theories on the geomechanical properties of different reservoir rocks to explain the causes of sand in the well flow. Much of this knowledge remained within the scientific domain, and its use within operational settings remained limited. An important part of the research project was therefore to create a correspondence between the shapes of *trended* sand data in historical sand incidents with different theoretical explanations for sand entering the well flow, diffracted digital sand into different kinds of events. In this manner, the phenomenon of digital sand is made richer and more nuanced and has multiple triangulated sources. Digital sand, then, never came down to "capturing" sand by a singular, perfectly accurate sensor. On the contrary, it emerged over time by adding layers, nuances, and interdependencies to the algorithmic phenomenon of digital sand. A steep incline in the trended data, for instance, corresponds with a sand avalanche where the reservoir collapses around the well. Repeated spikes of sand data against a background of an otherwise low sand influx correspond with another explanation (e.g., *slugging*), and so on. Each explanation came with its own particular mitigation strategies. Using the newly available trended sand data to identify an avalanche threatening to fill the pipes with sand, for instance, would be mitigated by *increasing* the well flow velocity to quickly transport the sand out of the pipes, instead of the old mitigation strategy of choking down and thus *reducing* it.

This opened up activity between the sand data trends and existing geomechanical theory to determine the causes of sand influx. In the aftermath of a sand incident, a production engineer explained, "It is fairly easy, really. The only thing we can do is to increase or decrease the production flow."

This, however, is a truth with modifications, as production engineers would monitor how the reservoir reacted to changes in increased/decreased fluid flows. As the same engineer later explained: "I continue to monitor the sand graph after instructing the offshore control room operators to choke down, at the same time monitoring for pressure increase in the pipeline." The production engineers would also continue to monitor how other operating variables behaved. A pressure increase, for instance, would be an early warning signal that the sand was starting to flow back. If this was taking place, the production engineer would instruct the offshore control room to increase the well flow velocity, seeking to lift remaining sand out of the well. What we see is that the trend opened up a form of interactivity with the reservoir, in which the production engineers could monitor the effects of their mitigating strategies and adjust them accordingly.

The gradual development of a richer, interactive algorithmic phenomenon of sand feeding a deeper understanding of the individual wells' personalities gave rise to new mitigation strategies. While the basics of this geomechanical theory are comprehendible to nonspecialists, the time it takes to do such a diagnosis is still beyond the offshore control room operators' temporal horizon. By visualizing sand data in a time series, the digital sand-monitoring system speeds up the feedback loop between petroleum professionals' actions and their effects on the phenomena in the physical environment they seek to regulate. With this, a new, interactive way of working with sand in the well flow emerged as production planning (which is the production engineers' domain) and production control (which used to be the control room operators' sole domain) were conflated. Consequently, mitigation responsibility was transferred from the control room operators to the production engineers, who now made decisions on how to operate parts of the offshore plant.

The trend came at the fore of sand monitoring and mitigation practice, as production engineers naturalized the practices of poking and triangulating sand data outlined earlier. They kept correlating sand data with temperature and velocity measurements to determine if sand alarms were triggered by other factors. They also continued to work seamlessly with both physical and digital representations, although their reliance on physical inspections remained less relevant. Instead, they used well flow sampling. The well flow sample is a physical sample tapped from the topside pipes and then taken to the laboratory and separated to determine whether or not there is sand in the fluids. These activities remained important, as NorthOil retained its zero-sand tolerance policy to prevent environmental and human damage. However, an adjacent field had moved on to using digital sand to monitor for equipment erosion, allowing the production organization to produce even with sand in the well flow, urging NorthOil to push forward.

PERIOD 4 (MID-2000S AND ONWARD): SAND AS A MACHINE LEARNING–BASED PREDICTIVE MODEL

It is the daily coordination meeting between the production, operations, and maintenance engineers located in the onshore production facility and the offshore process engineers and control room operators. The onshore engineers are gathered around a big conference table and linked with a similar-looking conference room at the offshore platform that also has several screens showing selected aspects of the status of the offshore platform (not unlike the bottom-most picture of figure 1.1). "Sand!" Howard, the meeting coordinator announces, as this is the item we have reached on the standardized agenda used for these meetings. "There was a sand incident in well A-6 last night," he continues. One of the attending maintenance engineers picks up on this, asking, "Do we need to inspect it?"

The "it" in question is the well's topside choke. Chokes are the valves that control fluid rates within the pipelines. Sand particles wear these valve openings down, degrading control over fluid rates. At worst, the valve casing is worn down, causing gas and fluid leaks. Chokes therefore tend to be replaced well before they wear out. However, replacing chokes has consequences. If choke erosion is suspected, the whole well is shut down as a precautionary strategy, causing a loss in productivity. Wells are otherwise shut down for scheduled maintenance only.

Everyone attending the meeting is of course well aware of this. They hesitate. For a second or two, the room goes quiet except for the whirring of computer-cooling fans. Ultimately, measurements and indications remain uncertain without physically inspecting the choke for erosion. Pete, the field's senior production engineer, breaks the silence, saying, "A-6 has a history of eating up its valves," which effectively makes the decision, knowing well the consequences in terms of productivity loss. Accordingly, Howard instructs the maintenance engineers to initiate an inspection of the choke, and the production engineers put A-6 on their list of nonproducing wells pending choke inspection.

The event with A-6 is later discussed over lunch. Kris, a senior research consultant with an international standardization organization, argues that "it is much like an egg of Columbus," referring to finding a simple solution for a seemingly intractable one, allegedly from when Christopher Columbus slightly crushed one side of an egg to make it stand still on a table. NorthOil, as with all oil operators on the Norwegian continental shelf, has until now vigorously pursued a zero-sand tolerance policy (due to the earlier explained risks to health, climate, and economic value). This policy, however, is being challenged. What Kris refers to as an egg of Columbus is a shift from preventing to managing sand erosion in the production system. What this implies is that wells, in situations like A-6, will not automatically be shut down whenever sand is detected (zero tolerance) to physically inspect the erosion of the choke. Instead, the well is to shut down only when the erosion of the choke is predicted to risk degrading process control. Hence, some sand is acceptable if "manageable"—that is, if the consequences of a loss of control are deemed noncritical. The crucial element in such a shift in sand policy is credible predictions of the erosion of chokes without actually (shutting down the well and) inspecting them physically. Together with researchers from NorthOil's R&D division, the sand-monitoring system vendor and the standardization organization developed an application to monitor the erosion state of chokes, pipelines, bends, and manifolds in the production system. Through tight collaboration they developed a predictive algorithm to simulate the erosion of valves and pipeline bends based on the offshore plant's real-time digital sand data. This allows a state to be simulated without being physically inspected.

In a first attempt, the predictive model in the simulation software was to rely directly on the IoT-generated sand data. As demonstrated earlier in this chapter (and, for exploration data, in chapters 4 and 5), this turned out to be a problematic assumption. A senior software engineer with the vendor admitted that when the "input data comes with a lot of uncertainties [and] the quality of the input data varies, the visualized output is basically meaningless."

After what was by all accounts considered a failed pilot test, NorthOil started another research project with the software vendor. Interestingly, and in the spirit of industrial science, NorthOil's research engineers did not go back to the drawing board to improve the reliability of the sand sensors. Instead, their knee-jerk reaction was to live with imperfection and instead find ways of dealing with it. Relying on the underlying predictive erosion model developed during the previous efforts, they decided to develop software functionality that, crucially, calibrated the simulations to another post hoc erosion measurement procedure already in place known as step-rate testing.

Step-rate testing is a calibration procedure used to determine the rate (volumes) of streaming from a single well into the topside processing plant at different degrees of choke valve opening (called steps). It is predominantly employed as part of the daily planning of production to ensure that the topside plant is used to its fullest processing capacity. The sheer force of the fluids streaming at high velocities wears the chokes down over time, increasing the valve opening the fluids stream through. The step-rate test is used to update the tabulation of choke valve opening and the rates to compensate for this wear and tear. Step-rate testing consumes invaluable production capacity as well as requires specialized equipment on the topside platform. It is therefore conducted only once or twice a year.

It was this existing calibration procedure that NorthOil's research engineers tapped into to calibrate the sand-based erosion predictions. Comparing the difference in measured fluid rates between the current and previous step-rate test, the engineers were able to develop erosion profiles to determine the current degree of erosion of a choke. The credibility of this regime was further strengthened when replacing chokes predicted to be worn out. Beaming with pride, the chief software engineer working on the condition-monitoring system stated, "We find that all chokes have eroded as predicted in all nine out of nine inspected."

Cultivating the organizational credibility of predicted choke erosion improved significantly when tethered to an existing calibration procedure (step-rate testing). However, it required substantial effort on the part of the production engineers to do this tethering to analyze the data to ensure calibration. Hence, it struggled to scale from a prototype to a routine tool. "Being able to drill down into the data and to actually correlate different data types is, of course, invaluable," a senior production engineer said before elaborating further:

> It gives us the chance of actually looking into the data and determine if we need to take action. As long as we monitor erosion on one, two or even a handful of wells, the tool is all we need. But on a field with 120 wells, that's another matter. We need some help to know which wells to pay attention to.

Again, the pragmatic instincts of industrial research came to the forefront. Rather than dismissing the prototype for predicting choke erosion due to excessive infrastructural work (see chapter 4), it was repurposed. Designed originally with the aim of generating predictions used to trigger maintenance interventions for individual wells, it was instead used to help onshore production engineers tasked with monitoring a portfolio of (hundreds of) wells. It was, accordingly, used as a screening or filtering device, filling the highly appreciated role of sorting the bulk of “unproblematic” wells from the smaller sample of wells warranting closer production engineers’ scrutiny:

> We decided to use a predetermined sand rate—that is we feed the algorithm with an expected level of sand content for every well—to determine how erosion prone each well is. What we do is to simulate the consequences of having this fixed sand rate on the different wells on the field. Say we monitor one hundred wells. For eighty of these wells this sand rate will have no erosion consequence [i.e., it will not, within the set period of time result in erosion that is outside safe levels]. For these there is no problem. But for the remainder twenty wells erosion may be an issue, and the production engineers need to pay particular attention to them. For these we have to ensure that the sand levels are so low as to not be a risk.

Sand monitoring as described above is used to prevent sand from incurring production loss while at the same time ensuring that the sand streaming through the system does not erode through pipeline bends and chokes. Production optimization is focused on optimizing the topside processing plant for maximal daily production volumes. Production optimization normally has a very short-term horizon. However, by using the sand-monitoring system’s predictive ability to simulate the erosion potential of different production scenarios, production engineers started to make long-term production optimization decisions. Predicting the erosion proneness of pipeline bends and chokes translates into production optimization practice in that production engineers simulate different scenarios for running the production system and then determine how current production decisions for short-term production optimization affects production optimization in the long term. They look at which parts of the system can run with a lot of sand for a while before having to be shut down. Through simulations, short-term optimization decisions come to be entangled with long-term planning as engineers use the simulations to project the consequences of their short-term decisions on the long-term viability of the field.

CONCLUSION

Rather than a dichotomy, what is striking in the above analysis is the relative effortlessness with which engineers navigate among real physical sand, plotted graphs of indicated sand, and predictive simulation models of sand. For all practical purposes, they all fill the role of sand in NorthOil operators' daily work practices. Their attention is the epistemic concern of knowing sand, regardless of its many manifestations.

In this sense the discourse on the ontological status found both in STS (van Heur et al. 2013) and in debates on sociomateriality in organization studies misses the point (Orlikowski and Scott 2008). As Cecez-Kecmanovic et al. (2014) point out, "After all, how many practitioners are going to be able to make any sense of, never mind care about, whether we adopt a critical realist or an agential realist ontology, and so on?" (826). The engineers at NorthOil are not concerned with what sand—really—is.

If chapter 1 made the analytic argument for dismantling the physical/real versus digital/virtual dichotomy, the current chapter provides vivid empirical elaborations. The realness of digital representations of physical sand is a highly acquired quality, not in any meaningful way read off through the abstract principle of liquefaction. The evolving work practices of the different offshore- and onshore-based engineers demonstrate what over time went into the domestication or naturalization of digital representations of *sand* (Silverstone and Hirsch 1994), the seamless meshing of digital representations with existing practices. Digital representations, gradually and with effort, get woven into the moral economy of the engineers' everyday lifeworld.

Specifically, this chapter underscores the importance of practices of interactive poking—"playing," as Lehr and Ohm (2017) phrase it—with the representations of sand to gain familiarity and confidence. The ongoing quest to craft, not simply assume, organizational credibility is dominated by institutionalizing the necessary calibration, triangulation, and tethering to existing routines and procedures that physically access the chokes without adding additional cost.

Digital Oil

Machineries of Knowing

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