# Co-materialization: Digital Innovation Dynamics in the Offshore Petroleum Industry

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**Abstract.** This paper empirically explores the concept of co-materialization to explain the digital innovation dynamics in offshore petroleum production. The central insight developed is that the very nature of subsurface processes and phenomena that may be monitored and controlled is transformed as offshore petroleum production is digitalized. The paper shows how digital technologies are intrinsic to this transformation as material reality and abstract concepts take on meaning together through digital technologies. The central dynamic driving this transformation is the process wherein digital technologies, physical phenomena, and work processes for monitoring and controlling these phenomena evolve together in continuous interplay.

**Keywords:** digital innovation, industrial transformation, materiality, performativity

## 1 Introduction

Digitalization[1] remained low within offshore petroleum production in the North Sea region well into the 1990s. Once available only by boat or helicopter, offshore installations in these inhospitable waters are today electronically available from the mainland. Massive developments of subsurface data communication cables have increased data transfer speed and capacity between offshore and onshore facilities [2]. Advances in data communication technology during the late 1990s enabled real-time communication between down-hole sensors and topside facilities, sparking a proliferation of remote sensor technologies connected in large sensor networks [3]. These sensor networks stretch across the seabed and deep into individual wells for entire oil fields. By connecting on- and offshore facilities through subsurface cables, these remote sensor networks have become constituent parts of a larger digital

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[1] This paper draws upon Tilson et al.'s [1] distinction between digitizing, understood as "the process of converting analog signals into a digital form", and digitalization, described as "a socio-technical process of applying digital techniques to broader social and institutional contexts that render digital technologies infrastructural" (p.750).

infrastructure [1] that the offshore petroleum industry has built up over the past decade or so.

Significant re-organizations of petroleum production in the North Sea have taken place during the same period, and personnel previously located at offshore installations have been moved to onshore operations centers [4]. Onshore personnel that used to focus on developing plans and recommendations that were handed over to offshore personnel to implement are today an integral part of daily offshore activities. With the availability of real-time sensor data and new engineering applications for visualizing and manipulating this data, onshore engineers can actively participate in monitoring, diagnosing, and controlling offshore processes. Since this new organization of offshore petroleum production is geographically distributed, communication technologies such as video conferencing, e-mail and instant messaging have become integral to the collaboration between offshore and onshore personnel [5].

The digitalization of offshore petroleum production is creating wakes of digital innovations [6] within the distributed network of petroleum companies, technology vendors, service companies and research institutions [7], and these wakes have spawned both actual and anticipated changes in the organizing logic [8] of the offshore petroleum industry. With a basis in the ongoing digitalization of the offshore petroleum industry, both the actual and anticipated changes have collectively functioned as an organizing vision [9] for the future organization of petroleum production. Heralded under different labels, such as e-Fields, Smart Fields, i-Fields, Digital Energy, and Integrated Operations, the core vision is fully digital oil fields in which mass volumes of sensor data are used for computer-assisted, or even completely automated decision-making.

This dominant view of the ongoing transformation of offshore petroleum production focuses on the innovation outcome, namely that of increased digitalization, though it says little about the dynamics driving the innovation processes related to digitalization. Yet, understanding these processes is important in order to achieve a better understanding of the relationship between digitalization and the ongoing transformations in the offshore petroleum industry. In a first step towards unpacking this relationship, this paper asks: *What are the dynamics driving digital innovation in the offshore petroleum industry?*

Through an analysis of empirical data from studies within the offshore petroleum industry, this paper explores a possible answer to the question. Building and elaborating upon the insight that digital technologies play an integral part in creating the materiality of the physical world [10], this paper contends that the impact of digital innovation in offshore petroleum production lies in a transformation of the fundamental relationship between work and the physical phenomena to be monitored and regulated. The central dynamic driving this transformation is the process wherein digital technologies, physical phenomena, and work processes for monitoring and controlling these phenomena evolve together in continuous interplay. *Co-materialization* is forwarded as a concept describing this process.

Co-materialization is offered as the main contribution of this paper. The paper contributes towards current developments of a performative agenda within IS research

[11]. This agenda is a response to continued calls to better account for the constitutive role played by computing technologies in studies of work and organizing [12-14]. Much of the existing work towards a performative agenda has, therefore, been to conceptualize the relationship between technology, work, and organizing through concepts such as sociomateriality [11] and imbrication [15]. This paper contributes towards the performative agenda by showing the necessity of expanding upon the notion of materiality to encompass the materiality of the physical world when studying the role of digital sensor technologies in transformations of work and organizing. This insight should be of general interest to researchers for the continued development of a performative agenda within both IS and IS-related fields.

The remainder of the paper is organized as follows: First, a section outlining a performative approach to studying digital innovation dynamics in offshore petroleum production is presented. The attention is then turned towards the methods and materials that the paper is based on. A case story is presented, before the concept of co-materialization is empirically elaborated based on the case story. The paper concludes by drawing some implications of the concept.

## 2 Digital Innovation and Materialization

While innovation is a much studied topic within the IS literature over the past decades, Lyytinen and Rose [16] observe that this literature is predominantly concerned with IS adoption and diffusion patterns. With basis in the observed lag between first availability of novel computing technologies and their adoption within organizations, the IS innovation literature has focused on how information systems come to be applied in novel ways to transform organizations' administrative, IS, or core business functions [17]. Focusing predominantly on the social processes related to adoption and diffusion dynamics, the IS innovation literature do not account for the constitutive role played by computing technologies as a driver in IS innovation.

The broader innovation literature has been concerned with what Dosi [18] refers to as the "'prime mover' of inventive activity" (p.148), i.e. innovation dynamic. These theories follow two broad categories: demand-pull and technology-push. Demand-pull theories see the marketplace and the identification of needs as the central dynamic driving technological innovation. These theories have been criticized for treating technology as a black box, failing to account for just how technology contributes to innovation. Technology-push theories, on the other hand, see innovation driven by technological development. Somewhat crudely put, this group of theories typically conceptualizes innovation as a linear process of science-technology-product. While technology development is the prime mover in technology-push theories, these theories tend to ignore the environmental feedback that shapes technologies as they are taken into use, which has been a central concern within the IS literature.

As such, neither the IS innovation literature, with its focus on adoption and diffusion patterns rather than innovation dynamics, nor the broader demand-pull/technology-push theories on innovation dynamics, offer much traction for studying the dynamics driving digital innovation in offshore petroleum production.

More recently, Tilson et al. [1] forward content digitizing coupled with functional convergence of computing and media platforms as the driving dynamic in transforming communication and media industries. Digitizing is also central to the transformation of offshore petroleum production. Drawing upon the works of Barad [19-21], Østerlie et al. [10] show how digital sensor technologies used in petroleum production play an integral part in creating the materiality of the physical world when digitizing physical phenomena. As such, digitizing the physical world is significantly different from content digitizing, which Tilson et al. [1] defines as "converting analog signals into a digital form" (p. 750).

Building upon the insight developed by Østerlie et al. [10], this paper further mines Barad's work to further develop a performative approach for analyzing the dynamics driving digital innovation in offshore petroleum production. Specifically, this section will, with some help from Rouse [22], elaborate on Barad's use of the concept of *materialization*. Barad uses materialization to describe the processes through which the world takes on meaning. Central here is that meaning is not inherent in the world, but rather, Barad assumes the position that meaning, which she refers to as "local intelligibility," is performed within phenomena in the world. Three elements in this position are of particular relevance here: the primacy of phenomena, material (re)configurations and discursive-materiality.

First and foremost, phenomena are the basic ontological unit in Barad's work: "phenomena are constitutive of reality" ([21], p. 205). The world exists independent of humans and our understanding of it; however, this does not mean that it is made up of pre-existing entities with more or less clearly delineated boundaries and properties that are to be grasped and represented. On the contrary: Rouse [22] contents that Barad's position is that "the world is articulated by overlapping, intra-acting phenomena, but most of these fail to disclose any pattern of local intelligibility" (p. 149).

If the world is not made up of delineated phenomena with fixed properties, what is it that we can have knowledge of? This is the point where Barad pushes performativity to encompass material reality. Instead of representations that mirror preexisting phenomena, phenomena take on meaning through processes of diffraction. While the world appears as phenomena with more or less clearly delineated boundaries and properties, these are not basic properties of the world. Instead, they are enacted through material (re)configurations in the world. When the world does disclose patterns of local intelligibility, i.e. when the world takes on meaning, it does so through particular material (re)configurations. Throughout her works, Barad uses various experimental scientific setups as pedagogic examples to illustrate such material (re)configurations:

> *[C]onsider an experiment in which light is scattered from a particle. The scattered light may be directed towards a photographic plate rigidly fixed in the laboratory and therefore used to record the position, or the light may be directed towards a piece of equipment with movable parts used to record the momentum of the scattered light. The first case essentially describes the process of taking a picture of the particle with a flash camera. In that case, the light is part of the measuring*

> *apparatus. In the latter case, the light's momentum is being measured and hence it is part of the object in question. ([19], p. 171)*

In this example, position is not a property of light as a preexisting entity with properties, but rather is enacted through the scientific instrument setup. Yet, the boundary between light as a phenomenon with properties such as position or momentum to be measured, and the instrumental setup, is not fixed either. When measuring momentum, light is part of the instrumental setup, and to this end, Barad argues that scientific instruments are not external to the reality being grasped, but are always part of the material (re)configuration that makes reality intelligible. But, if "the belief in the power of words to mirror preexisting phenomena" ([20], p. 802) is misguided because phenomena are enacted through material (re)configurations, what then is the function of concepts such as position and momentum?

This leads to the third element of Barad's concept of materialization: discursive-materiality. Instead of refuting the dualism between discursivity (in this example understood as abstract concepts such as position and momentum) and materiality, Barad posits that phenomena are discursive-material. In so doing, Rouse [22] observes that Barad includes concepts as part of the material (re)configuration that makes reality intelligible: "the natural world only acquires definite boundaries and concepts only acquire definite content, together" (p. 146). Barad offers an interpretation of Bohr's quantum physics philosophy to illustrate this point. For Bohr, position is not a property of a particle, nor is it an abstract concept. Instead, the concept of position only has meaning through an experimental setup or a material (re)configuration in Barad's vocabulary, with fixed rulers and a particle.

To summarize, with a basis in an ontology of phenomena, reality takes on meaning through discursive-material (re)configurations in the world, a process Barad refers to as materialization. Nyberg [23] juxtaposes Barad's work with actor network theory [24]. He observes that whereas ANT seeks to explain how phenomena become stable, Barad retains the poststructuralist sensitivity towards reality as becoming rather than being. As such, her work emphasizes the fluidity and constant unfolding character of phenomena.

A central premise for studying digital innovation in offshore petroleum production is that the physical phenomena that petroleum professionals monitor and control are physically inaccessible to human inspection. It is therefore meaningless to distinguish between material reality, understood as the stuff the world is made up of [25], and the digital technologies for knowing about it. Thus, the attraction of materialization for studying digital innovation in offshore petroleum production lies in Barad's formulation of a performative ontology that creates no such separation between phenomena and the physical arrangements for knowing about them.

## 3 Methods and Materials

This paper draws upon data collected through two consecutive studies within the Norwegian petroleum industry. The first of these studies did not focus on digital innovation, but rather on ICT use for safe and reliable petroleum production. This study was conducted as an independent part of a larger joint industry research and development project (JIP) within the Norwegian petroleum industry [26]. The JIP is a form of generic project organization used within the petroleum industry to facilitate cooperation between petroleum companies, the vendor industry and research institutions to build competency and develop technologies regarded as particularly critical to the industry as a whole. The particular JIP reported from here gathered participants with long and extensive experience from the ongoing digitalization of the North Sea in order to study the feasibility of expanding petroleum production into the polar region. I participated in workshops and meetings organized regularly within the JIP. Seeing the JIP as a rich site for learning more about the ongoing digitalization of offshore petroleum production, I approached project workshops and meetings as fieldwork using breaks and after hour activities to learn more about other project participants' experiences from the ongoing digitalization of offshore petroleum production.

In parallel with attending project activities, I conducted 10 months of ethnographic fieldwork [27] in the onshore operations center of an international petroleum company operating in the Norwegian sector of the North Sea. This operations center houses the onshore personnel of several offshore petroleum fields. Onshore and offshore personnel work closely with each other, communicating through different media such as instant messaging, e-mail, phone, and video conferencing. At the time of conducting the fieldwork, the petroleum company was in the final stages of implementing a new engineering application for the real-time monitoring of wells for use in the onshore operations center. I had, therefore, collected quite a lot of data on the relationship between digitalization and work transformation when asked to do the second study this paper builds upon. I had even developed the outlines of a model on digital innovation dynamics as part of the analysis for the first study.

Digital innovation in offshore petroleum production was the topic of the second study. Financed as an independent study, I was asked by the same petroleum company where I had previously conducted ethnographic fieldwork to come up with policy advice to improve the organization's ability to implement research-based software in their operational units. Deciding to base this study on the model of digital innovation dynamics I had previously outlined, I conducted a total of 24 interviews with people who had been involved in developing new digital technologies used within the petroleum company: 13 researchers and 4 software engineers working in the corporation's R&D division, 3 engineers from different operational units who had been the customer for new digital technologies, 1 engineer working in the corporation's central IT division, as well as 3 software engineers working in vendor companies who develop new digital technologies put to use within the petroleum company under study. The interviews focused on the respondents' experiences from research-based software development projects. Instead of focusing on single projects, I inquired about general experience. Nevertheless, throughout the period of the interviews, I acquired insight into a number of specific projects and digital technologies.

This paper, therefore, draws upon a diversity of materials. I made daily field notes [28] throughout the ethnographic fieldwork in the onshore operations center. Jotting down notes in a pad throughout the day, I would transcribe the field notes during periods of calm or latest the same day upon returning from the fieldwork. Similarly, I made field notes during JIP project workshops and meetings, which I transcribed later the same day. Conducting the first study as a grounded theory study [29], I coded the field notes shortly after writing them up, writing theoretical memos to record conceptual insights emerging during coding. In addition to the field notes taken during the first study, the theoretical memos related to innovation were used as materials for the analysis presented in this paper. From the second study I have transcribed each of the interviews conducted. I also conducted a document search of OnePetro (http://www.onepetro.org) to collect supplemental data on the projects and technologies mentioned during the interviews. OnePetro archives all papers published through the Society of Petroleum Engineers' conferences and journals, making it a key source for reports on the experience and development of new technologies from the global petroleum industry.

The concept of co-materialization emerged from the analysis a large number of projects and technologies developed over the past 20 years. For the ease of presentation, I choose to empirically ground the elaboration of co-materialization in a single case story. This particular case has been chosen because it intensely manifests central properties and dimensions of co-materialization.

## 4 Case Story: Predictive Maintenance of Topside Chokes

Petroleum is produced from hydrocarbon molecules contained within fluids trapped in subsurface reservoirs. On the Norwegian Continental Shelf (NCS), a subsea plateau that forms the Norwegian sector of the North Sea, these reservoirs are located thousands of meters beneath the seabed. Wells have been drilled to drain the fluids containing hydrocarbon molecules out of the reservoirs. Reservoir pressure pushes the fluids, referred to by petroleum professionals as the well flow, out through the wells and through kilometers of pipelines leading topside towards an offshore production platform. Onboard the platform, a petrochemical processing plant separates crude oil and gas from the hydrocarbon molecules contained within the well flow. The gas is exported by pipeline to onshore refineries, while supertankers feed refineries across the globe with crude oil from the NCS.

This section outlines the major steps towards one of the more recent innovations in offshore petroleum production: predictive maintenance of offshore chokes. It starts with an outline of sand influx, the basic problem addressed by predictive maintenance. It then outlines the major developments towards predictive maintenance of offshore chokes. The purpose is to outline the case story that forms the backdrop for the discussion of co-materialization as a concept describing and explaining key dynamics driving digital innovation in offshore petroleum production.

## 4.1 Sand Influx and Sand Control

NCS reservoirs are typically found within geological sand stone layers. The porous sand stone structures function as sponges, trapping fluids containing hydrocarbon molecules. Over time, as increasing amounts of fluids are drained out of a reservoir, changes in the fluid balance may cause these sand stone structures to loose integrity. As the sand stone looses integrity, large areas of the reservoir start crumbling and may even collapse. Sand particles from the crumbling reservoir is then swept along with the fluids that are drained out of the reservoir, into wells and through the pipelines towards the topside platform.

Sand swept along with the well flow end up as sand deposits in the petrochemical processing equipment on the topside platform. Sand deposits stand the danger of contaminating the crude oil and thereby degrading its quality. In addition, sand clogs up the processing equipment. Parts of the processing plant have to be taken offline to clean the processing equipment of sand deposits. This reduces the plant's processing capacity for the duration of the cleanup procedure. More critically, though, sand particles create a sand blasting effect on chokes (the valves used to control fluid flow rates within the piping) and in pipeline bends as they are swept along with the fluids streaming at high speeds through the piping. Sand can, in extreme cases, erode through piping and choke casing and thereby puncturing the equipment. A punctured pipeline subsea may cause immense environmental damage as oil gushes into the ocean. On the topside platform, a punctured pipe or choke casing will send high-speed fluids jetting onto the deck. This is a significant safety risk as the high-speed fluids may cause human injury or even death. The well flow also contains gas. Punctured equipment topside will, therefore, also cause a gas leak. Leaking gas is considered among the most dangerous situations on a petroleum installation as it may ignite and explode.

Sand problems are not particular to the NCS. Referred to as sand influx, sand-related problems are reported in the American petroleum literature as early as the late 1940s. Sand influx as a concept describes the physical processes in the subsurface reservoir that cause sand to be swept into the well. To this end, well screening technologies for preventing sand from entering wells have been developed. It comes with a set of technologies and work practices aimed at preventing sand from entering wells. These technologies and work practices are collectively referred to as sand control. Sand control routines builds on the premise that wells can only produce at rates where there is no sand influx. As such, these routines focus on establishing the maximum fluid flow rate where sand is not swept from the reservoir into the well. While this may significantly reduce the production rates of a single well, this is usually not a significant problem as long as only a few wells produce with such restrictions.

## 4.2 Sand Content and Sand Monitoring

Sand deposits started appearing in the topside petrochemical processing equipment of offshore platforms on the NCS in the late 1980s early 1990s. By then, the fluid balance within reservoirs on fields developed in the early 1970s and 80s was causing sand stone formations to collapse. Production restrictions related to producing at maximum sand free rate on a single well has limited impact on a field's overall production volumes. However, when a large number of wells experience sand influx it significantly reduces the field's overall production capacity. This was the situation, or at least the prospective situation, for an increasing number of fields on the NCS at the beginning of the 1990s.

Sand monitoring emerges in the mid 1990s as a response to this problem. Sand monitoring builds on the premise that limited amounts of sand in the well flow constitutes no significant risk to safety or operations. Instead of establishing the maximum sand free rate on a well, sand monitoring seeks to ensure that wells produce within what is called maximum safe sand rate. However, producing with maximum safe sand rate requires real-time monitoring of the amount of sand in the well flow.

Sand monitoring as an alternative strategy for dealing with the effects of sand is proposed in a period where early digital sensor technologies are being put in use on offshore platforms. In parallel with developing safe operational constraints for producing with sand in the well flow, different digital sensor technologies for quantifying sand content were being experimentally developed. Several vendors sought to offer this technology, but in the end acoustic sand sensors are chosen. Acoustic sand sensors detect the ultrasonic sounds of sand particles hitting the inside piping in bends. Based on an algorithm that combines well flow velocity with the frequency of ultrasonic sound signals, the sand sensor quantifies the number of sand grains passing across it per second.

Sand monitoring requires significant changes in the operating conditions for the platform. Producing with sand in the well flow increases wear and tear on pipes and chokes. Sand monitoring is therefore coupled with more frequent and extensive inspections and maintenance of pipes and chokes. Sand monitoring required pipe and choke vendors to develop new inspection and maintenance frequencies, and changes in the maintenance regimes of the subcontractors in charge of plant maintenance.

## 4.3 Erosion Potential and Predictive Choke Maintenance

Chokes are used to control fluid rates within the pipelines. The valve opening and thereby accuracy degrades as the choke wears out. This gives offshore operators less control over fluid rates, making it increasingly difficult to regulate the production process in such a way that it optimizes the plant's processing capacity. Chokes on fields with the sand monitoring therefore tended to be replaced well before they were worn out. This is expensive and causes unnecessary downtime.

By the turn of the millennium petroleum companies operating on the NCS had started building up onshore operations centers. Data communication capacity between on- and offshore installations was steadily increasing, and operators were exploring the possibilities of involving onshore personnel more closely with daily offshore activities. A key task for the onshore personnel was to optimize daily production. Production optimization seeks to prioritize between wells in such a way that the offshore petrochemical plant's processing capacity is used most efficiently within the restrictions incurred through the gas and crude oil export capacity.

As part of these efforts, one operator along with a software vendor and an engineering company joined forces to develop predictive choke maintenance to give onshore engineers better control with the accuracy of the offshore chokes used to optimize production. This was developed for a field already running with sand monitoring strategy. To this end, the engineering company developed a set of models describing and prescribing the degree of wear and tear on individual wells over time depending on the amount of sand having passed through the choke. This, they called erosion potential. The software vendor developed a tool that used these models together with sand sensor and other data sources to predict the current state of offshore chokes.

While the basic models for erosion potential remained unchanged, the software tool underwent a number of revisions. The greatest challenge was related to poor data quality of the input data. A number of visualizations and work processes were developed to allow onshore engineers to determine accuracy of the choke erosion models.

## 5 Discussion: Digital Innovation and Co-materialization

With basis in the case story above, I will now explore a possible answer to the question 'what are the dynamics driving digital innovation in offshore petroleum production?'. The difference between innovation, on the one hand, and technology adoption and organizational change in general, on the other, is that some form of novelty accompanies innovation [16]. To answer the research question, we, therefore, first have to establish what constitutes novelty in the case story. Having established this, we can then turn our attention to the dynamics driving digital innovation in offshore petroleum production.

With the organizing vision of fully digital oil fields in which mass volumes of sensor data are used for computer-assisted, or even completely automated decision-making, most of the petroleum industry literature forwards novel digital technologies as 'prime-mover' [18] of the ongoing transformation of offshore petroleum production. In the case story above, however, neither the acoustic sand sensor that measures sand in the well flow nor the software developed to monitor erosion on individual offshore chokes is based on novel digital technologies. The acoustic sand sensor is based on a technology for detecting ultrasonic sounds. While never previously used to measure sand content in fluids, the technology itself was, at the time, by no means a novel technology. Rather, it had been developed for other uses and used for a number of applications prior to developing digital sensors for detecting and quantifying sand. Similarly, the software developed to predict choke erosion was crafted around a series of familiar visualization techniques such as plotting data in graphs for comparison between data sources and breaking down the physical infrastructure in a tree hierarchy to ease navigation.

Instead, novelty in the case story lies in a transformation of the very nature of subsurface processes and phenomena that may be monitored and controlled. The case story above traces two such transformations: the transformation of sand and of erosion from approximated to quantified phenomena. We can use the transformation of sand from an approximated, delayed action phenomenon to sand as a real-time, quantifiable characteristic of the well flow to exemplify this. Prior to the introduction of digital sand sensors, sand in the well flow materialized as accumulated deposits in the processing equipment. It would take hours from measures to limit sand influx had been taken before sufficient deposits had accumulated in the processing equipment so that offshore personnel could determine the effect of their actions; sand was a delayed action phenomenon. Offshore personnel would, furthermore, refer to sand deposits in approximate and relative terms such as significant or small amounts of sand observable when cleaning up the processing equipment.

Digital technologies are intrinsic to transforming sand from an approximated, delayed-action phenomenon to a real-time, quantified characteristic of the well flow. Physical phenomena materialize through complex discursive-material performances that involve undifferentiated matter, physical artifacts and digital technologies. Sand content emerges through the material setup of an acoustic sand sensor, along with a pipeline bend, and the undifferentiated matter of the well flow rushing from the well towards the topside platform. The acoustic sand sensor is mounted on the outside of this bend. The well flow creates a sound as it hits the outer bend of the piping, where the sand sensor is mounted, at high speeds. The acoustic sand sensor is designed to isolate the sound of solid particles hitting the piping, and transforms this sound into a digital signal. Through laboratory experiments, the sensor vendor had developed an algorithm that combines well flow velocity with frequency of ultrasonic sound signals to calculate sand content, measured as grains of sand passing across the sand sensor per second. The acoustic sand sensor's controller software implements this algorithm to transform the digital signals generated by the acoustic sand sensor into a measurement of sand content. Sampling the digital signals each second, the material setup of acoustic sand sensor, controller software, piping, and well flow performs sand as a real-time, quantified characteristic of the well flow.

In this analysis, sand content as a quantifiable characteristic of the well flow is not a property of the physical world simply waiting to be represented. Instead, it is performed through the material setup where digital technologies – both acoustic sand sensor hardware and controller software – play a constitutive role in creating the materiality of the physical world [10]. As such, sand content is not merely an abstract concept (i.e. discursive). Rather, material reality and abstract concepts take on meaning together through digital technologies; they co-materialize.

This is not to be interpreted as a form of radical constructivism claiming that sand in the well flow as a figment of social construction. Such a position would reduce physical phenomena to being purely discursive. The argument pursued is, on the contrary, a refutation of reducing physical reality to constructs and representations, and instead to offer a realist analysis of how the world takes on meaning through the use of digital technologies. There were undeniably solid particles in the well flow before introducing the acoustic sand sensor, with accumulated sand in the processing equipment being a testament to this. Yet, it is through the discursive-material reconfigurations outlined above that sand content, as a quantitative characteristic of the well flow, comes to be performed as a pattern of local intelligibility, to use Barad's terminology.

Having established what constitutes novelty in the case story, we can turn our attention towards the dynamic driving digital innovation in offshore petroleum production. Sand had been a well-known operational problem within the global petroleum industry for almost half a century when platforms on the NCS started experiencing sand influx in the late 1980s. While measures for handling sand in the well flow along with research on reservoir geology to better understand the causes of sand influx had been in continuous development since the 1970s, it is with the advent of digital technologies in the 1990s that sand content emerges as a real-time, quantified characteristic of the well flow. This does not mean that some sort of technological imperative drives the emergence of sand content. An engineer working with a vendor company offering a sand sensor technology competing with the acoustic sand sensor in the case story, explained that their sand sensors built on a technology that the vendor had developed for significantly different purposes. They had never thought of using the technology to detect and quantify sand. Yet, when petroleum companies operating on the NCS started developing sand content as a concept, the vendor saw the possibility of adopting their technology to implement the sand content concept.

As such, digital technologies emerge as part of an evolving understanding of how to regulate subsurface processes and phenomena. Subsurface processes play an important role in shaping this understanding. Digital sensor technologies for quantifying sand in the well flow emerges at a point in time when a growing number of oil fields on the NCS were beginning to experience significant reduction in production capacity due to sand influx. Petroleum companies came to identify sand control as a significant production limitation to be addressed. Sand monitoring, as a concept emerges from the convergence of aging oil fields on the NCS and the technological possibilities of technological developments at the time. The senior research engineer commonly attributed as the key originator of the sand monitoring concept participated in the industry R&D project that this paper draws from. He described the sand monitoring strategy as an egg of Columbus: once formulated, everybody was wondering why nobody had come up with the idea before. Clearly proud to be attributed as the originator of sand monitoring, he carefully pointed out that formulating the concept was "a matter of timing". The timing was right in that increasing computerization of offshore installations opened up for the possibility of instrumenting the production process with digital sensors, which made the production restrictions caused by sand control to be a solvable problem.

The evolving understanding of how to regulate subsurface processes and phenomena emerges from recognized needs and relevant technologies for responding to these needs. Sand content co-materializes with technologies for measuring sand content and sand monitoring in a space of possibilities where changes in fluid distribution in maturing reservoirs lead to increased sand influx in wells, where existing sand control strategies significantly reduce production volumes on fields with much sand influx, and where measuring sand content is technologically feasible. It is, therefore, possible to say that recognized needs and relevant technologies for responding to these needs co-materializes out of the same space of possibilities.

## 6 Conclusion

This paper has empirically explored the concept of co-materialization to explain the digital innovation dynamics in offshore petroleum production. The central insight developed is that the very nature of subsurface processes and phenomena that may be monitored and controlled has been transformed as part of digitalizing offshore petroleum production. The paper has shown how digital technologies are intrinsic to this transformation through a process where material reality and abstract concepts take on meaning through digital technologies. The central dynamic driving this transformation is the process wherein digital technologies, physical phenomena, and work processes for monitoring and controlling these phenomena evolve together in continuous interplay.

As such, this paper offers an interpretation of the ongoing digitalization focusing on change processes. This supplements the focus on innovation outcome predominant in the organizing vision of fully digital oil fields (see Section 1). While this organizing vision has been central to securing top-level commitment to the massive investments required for developing the digital infrastructure and making the organizational changes required to transform offshore petroleum production. Now that the infrastructure is more or less in place, the industry is entering a new phase: that of capitalizing on the digitalization. Co-materialization offers a perspective that may contribute towards this second phase. By emphasizing the creation of new phenomena forms the thrust of digital innovation, co-materialization suggests that focus for this second phased of digitalization should lie on finding new ways of using existing data sources to create phenomena that may be regulated in order to improve and optimize production.

Through the concept of co-materialization, this paper suggests that digital innovation not only changes the nature of work but the very phenomena to be regulated through technology and work. Common to both sand monitoring (Section 4.2) and predictive maintenance (Section 4.3) is that they constitute a fundamental shift in the industry's relationship to the materiality of offshore petroleum production. Both sand monitoring and condition monitoring constitute a shift away from static towards a more dynamic relationship with the materiality to be monitored and controlled. Such a shift is a common denominator to digital innovation in offshore petroleum production. This may suggest that the ongoing digitalization of offshore petroleum production constitutes a shift towards an increasingly dynamic relationship that transforms the offshore petroleum industry as it redistributes competency within petroleum companies, as well as between petroleum companies and other actors within the offshore petroleum industry on the one hand, while transforming the nature of work, technology and organizing within the offshore petroleum industry on the other. This, however, will have to be explored further in later publications.

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