Staging with Objects

Managing Technology Development in the Off-Highway Mobile Hydraulic Industry

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MANAGING TECHNOLOGY DEVELOPMENT IN THE OFF-HIGHWAY MOBILE HYDRAULIC INDUSTRY

BY
CHARLES ANTHONY BATES

DISSERTATION SUBMITTED 2020

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

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CV

Charles Anthony Bates is the Global Head of BU Motors Technology in the Work Function Division at Danfoss Power Solutions (DPS), where he has worked with the development of new component, material, product and process technologies associated with the design, verification and production of hydraulic motors and steering units since 2005. His Industrial PhD is a collaboration between DPS and the Sustainable Design and Transition Research Group in the Department of Planning at Aalborg University Copenhagen, and was made possible with funding from Innovation Fund Denmark. In addition to his social science research, he has (co)authored multiple patent families and journal articles in the fields of hydraulics and tribology.

Charles Anthony Bates holds a BSc. Engineering in Mechatronics from the University of Southern Denmark and a Master of Professional Communication from Roskilde University. He is a citizen of the USA (born) and Denmark (naturalized) and presently divides his time between DPS facilities in Zhenjiang, in the Jiangsu Province of China, and Sønderborg in Denmark.

ENGLISH SUMMARY

This industrial PhD is based on my ongoing 15-years of experience as a technology manager and engineer at Danfoss Power Solutions, an established leader in the off-highway mobile hydraulic industry. The research question, **how staging with objects can contribute to managing technological innovation across specialized knowledge networks**, was developed in response to both my *own* limited understanding of the micro-processes involved in defining, communicating and implementing technical minutia into the wider organizations of which I am a part, and the paucity of scholarship supporting such skilled industrial practices. Though innovation management literature is diverse in scope, there is a prevailing macro-perspective – emphasizing 'process models' and 'frameworks', 'strategies' and 'countermeasures' to help industrial top-leadership define and achieve 'successful innovation'. Most management tools purporting to serve processes of innovation are limited to epistemological considerations, á la how managers and engineers obtain knowledge and leverage this knowledge in action. Questions or even viewpoints pertaining to the nature of the realities within which these actors operate are mostly considered tangentially – discussing what 'good' *management* or *innovation* are or provide in assumedly transparent contexts – if at all. To address these limitations, I draw from STS scholarship on 'objects' and 'staging', and empirical material from auto-ethnographic studies spanning two cases, to describe industrial technology development as a process of network formation including actors and objects that are shaped by, and in turn shape, how *other* networks are constituted, configured and transformed (i.e. *staged*).

The dissertation culminates in a methodological framework for 'staging with objects' as an industrial practice that answers the research question in the context of three key dimensions of this practice: **1) Facilitating engagement across specialized networks; 2) Fostering common points of reference and alignment of interests across diverse stakeholders; and 3) Helping actors to articulate and mobilize resources within their organizations**. This methodological framework takes root in assumptions that epistemological considerations – regarding the *means* by which technology managers and engineers can know or act – are inseparable from ontological *reflections* about how things are manifested and associated. Previous STS scholarship has shown conceptualizations of objects – including *boundary objects*, *intermediary objects*, *(re)writing devices* and *calculative devices* – adept in making sense of different types of specific work arrangements. What makes this framework novel is the *localization* of where and how this sensemaking process takes place. Moving beyond academic utilizations of these concepts to analyze and understand empirical material *after action takes place*, the dissertation presents how these same concepts can be utilized by skilled practitioners to analyze and ultimately shape processes of technology development in real-time, from the *midst* of action.

DANSK RESUME

Denne erhvervs-ph.d. er baseret på min 15-års erfaring som teknologileder og ingeniør hos Danfoss Power Solutions, en førende virksomhed indenfor mobile hydraulisk industri. Afhandlingens forskningsspørgsmål – **hvordan iscenesættelse med objekter kan bidrage til at styre teknologisk innovation på tværs af specialiserede videnetværk –** udspringer af både min begrænsede forståelse af de mikroprocesser som er med til at definere, kommunikere og implementere detaljerne i de teknologiudviklingsprocesser, som jeg indgår i, og manglende forskning om industriel praksis. Skønt megen af innovationsledelseslitteraturen understreger vigtigheden af 'procesmodeller', 'rammer', 'strategier' og 'modforanstaltninger' har det et makroperspektiv på *teknologiudviklingen* – den fokuserer på hvad topledelsen skal gøre for at opnå 'succesfuld innovation'. De fleste managementværktøjer, der påstås at understøtte innovationsprocesser, baseres på epistemologiske overvejelser om, hvorledes teknologiledere og ingeniører opnår viden og udnytter denne viden. Spørgsmål om hvilke virkeligheder disse aktører opererer behandles for det meste perifert – fokus rettes primært mod hvad 'god' *ledelse* eller *innovation* er, og mindre mod hvad dette fordrer. For at adressere disse begrænsninger, trækker jeg på indsigter fra Science and Technology Studies (STS) om 'objekter' og 'iscenesættelse', samt på mine auto-etnografiske studier af industriel teknologiudvikling i to cases. Dette betragtes som en netværksdannelsesproces, der inkluderer aktører og objekter, som gensidigt former hvordan *andre* netværk er konstitueret, konfigureret og transformeret (dvs. *iscenesat*).

Afhandlingen bidrager med en metodologisk ramme for 'iscenesættelse med objekter' som en industriel praksis, der besvarer forskningsspørgsmålet i sammenhæng med tre nøgledimensioner i denne praksis: **1) At facilitere engagement på tværs af specialiserede netværk; 2) At fremme fælles referencepunkter og tilpasning af interesser på tværs af forskellige interessenter; og 3) At hjælpe aktører med at artikulere og mobilisere ressourcer i deres organisationer.** Denne ramme er baseret på antagelsen om, at de epistemologiske overvejelser mht. metoder teknologiledere og ingeniører må have er uadskillelige fra ontologiske refleksioner om, hvordan tingene manifesteres og associeres. Tidligere STS-studier har vist at objekter – inklusive *boundary objects, intermediary objects, (re)writing devices* og *calculative devices* – er med til at skabe mening om forskellige arbejdssituationer og -arrangementer. Det nyskabende ved afhandlingens forståelsesramme drejer sig om *lokaliseringen* af, hvor og hvordan denne sensemaking proces finder sted. Ved at flytte fokus fra en akademisk anvendelse af disse koncepter til at analysere og forstå det empiriske materiale *efter handlingerne* har fundet sted, argumenterer jeg for, hvordan disse koncepter kan bruges af praktikere til at analysere og forme teknologiudviklingsprocesser 'in real time', *midt* i handlingen.

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It was an honor to collaborate with my co-authors: Christian Clausen and Joakim Juhl.

My wife’s generosity and patience continue to inspire me.

Thank you all!

Charles Anthony Bates
Sønderborg, 31 July, 2020

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1. INTRODUCTION

Tall and lean, EJK bends and twists his right hand as he speaks, like he is trying to position an invisible pencil to write on the inside bicep of the same arm.

> As managers, we'd like to assume it's our hand manipulating the tools we're given. […] But they manipulate us too. The ways these tools can be gripped and positioned decide how our hands move.[1]

EJK is an engineer with over 15 years of international experience. He is also, at the time, the highest-ranking project manager in our business unit. While his contortions provide a visceral demonstration of the more abstract conundrums to which he is accustomed, it was his words that really surprised me.

My immediate (albeit arrogant) reaction was "mission accomplished". I'd spent the last 18 months discussing relational aspects of enactment with my colleagues. Carefully explaining how "materially heterogeneous relations [could be] analyzed with semiotic tools" (Law 2009: 144) towards improving engineering practice. To date I'd imagined me providing my colleagues with a vocabulary by which they could reflect on the agency of the objects with which we interacted – be they prototypes, test-specifications or the process models. Perhaps, to some extent, this was true. Certain words had made their way into everyday conversation. Notions like 'commissioning' (Vinck et al. 1996), 'enrollment' and 'mobilization' (Callon 1984), and 'staging' (Clausen and Yoshinaka 2005, 2007, 2009; Yoshinaka and Clausen 2020, forthcoming) had trended sporadically. Still, reconsidering my colleague's words, I realized that accommodating the performativity of objects was more than an abstraction for EJK. It was part and parcel of his practice. EJK is well-capable of reflecting over the ways his objects shape possibilities for action, be these objects chosen or assigned. EJK can delimit or expand possible means of action as he negotiates their effects in scheduled and *ad hoc* discussions across a diversity of stakeholders. More importantly, he does this every day; intuitively and reciprocally manipulating disparate objects to accommodate dynamic goals over which he has varying degrees of control.

At that moment with EJK, I could clearly see the company's engineering practice as a rather grand piece of improvisational theatre[2], orchestrated around and with a variety of (im)material objects, including functional conceptualizations, patents, process models, prototypes, standards and test-rigs. Within these staged settings, diverse

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[1] Edited for clarity and brevity from a conversation on 14 January 2019.

[2] The forthcoming book chapter by Vinck and Tanferri (2020) is perhaps the most comprehensive analysis of the theatrical staging metaphor to date.

actors are cast and directed towards overarching goals – the intricacies of which are defined by the actors themselves, via planned and spontaneous interactions with company sanctioned tools designed to perform across an assortment of presupposed contexts – as established and novel technologies are reciprocally negotiated. I hope the complexities and excitement of this endeavor are equally visible for the reader, as I structure this dissertation around efforts to develop a methodological framework addressing how objects can be staged by technology managers and engineers to support processes of technology development in industry.

1.1. MOTIVATION

I have been employed as an engineer in the Work Function Division (WF) at Danfoss Power Solutions (DPS) since 2005, working with the development of new component, material, product and process technologies associated with the design, verification and production of hydraulic motors and steering units.[3] I began leading technology development projects in Denmark in 2006 and in 2013 I was awarded my first management position as Technology Portfolio Manager. In 2014 I was concurrently appointed to Technology Team Leader, and in 2017 I left both positions to serve as Manager Engineering Technology for the Motors BU. In 2020 I accepted the position of Global Head of BU Motors Technology on a Chinese contract.

While 15 years of industrial engineering practice have provided me with unique and published insights into technical minutia spanning statistics (Bates 2008, 2014s), tribology (Bates et al. 2020; Furustig et al. 2015a, 2015b, 2016) and hydraulic circuits (Arbjerg et al. 2018a, 2018b; Bates et al. 2018a, 2018b, 2018c, 2018d, 2018e, 2018f; Frederiksen et al. 2019), the appointment to Technology Portfolio Manager in 2014 exacerbated (what I viewed as) personal shortcomings outside certain fields of engineering. Shortcomings that seemed to hinder my efficacy in tack with growing responsibilities. That I lacked a theoretical foundation wherefrom I could reflect over social interactions in my working practice was particularly apparent. Hoping to move beyond what I considered “facilitation by intuition”, I enrolled in the Danish Master of Professional Communication program at Roskilde University.

This program was my first introduction to what Williams and Edges (1996: 865) term the ‘Social Shaping of Technology’ (SST) – which in contrast to approaches that only focus on impacts of technological change examines “the content of technology and the particular processes involved in innovation” – and Actor-network theory’s “material-semiotic tools, sensibilities, and methods of analysis that treat everything in the social and natural worlds as a continuously generated effect of the webs of

[3] With over 2b Euro in annual sales, 25 factories in 12 countries and ~6700 employees, DPS is a leading player in the construction, agriculture and material handling industries and consistently ranks first or second in sales within these markets (Danfoss A/S 2019).

relations within which they are located" (Law, 2009: 141). The program also introduced me to the work of the 'Montreal School' on organizational communication (Cooren 2010; Cohen and Sandler 2014) and to Clausen and Yoshinaka's 'staging' notion (2005, 2007, 2009; Clausen and Gunn 2015; Yoshinaka and Clausen 2020, forthcoming – see Chapter 2), which shaped my MA thesis on how dialogue can affect connections between strategies, actors and objects situated to perform across distributed spaces of technology development. In addition to a theoretical ballast for self-reflection, the program provided me with practical tools for pursuing communication as a craft. These newly acquired skills markedly improved my efficacy in defining, planning and executing technology development projects, and were among reasons given for the promotion to Manager Motor Engineering Technology upon my graduation.

Still, the intricacies of interaction between actors and objects, and the mechanisms by which these interactions unfold in processes of technology development continued to elude me. I became frustrated with my limited understanding of my own practice in defining, communicating and implementing technical minutia into the wider organization. Furthermore, I failed to recognize these everyday challenges in a mostly prescriptive body of 'innovation management' scholarship which purports to service industrial managers and engineers. I thus reasoned that an Industrial PhD focused on innovation as a complex process of 'translation' (Callon 1984; Law 2009) with outset in my own practice as a technology manager and engineer was the best remedy. This proved easier said than done – for reasons I return to in Chapter 6.

1.2. TECHNOLOGY DEVELOPMENT IN PRACTICE

It has become commonplace for leading industrial organizations to articulate their abilities to innovate in key promotional slogans: 'Engineering Tomorrow' from the Danfoss Group, 'Imagination at Work' from GE, 'Ingenuity for Life' from Siemens, 'Driving Change' from Novo Nordisk and 'Science Applied to Life' from 3M. Still, with few exceptions (see Juhl 2013, 2016), little is known of "the role of formal reasoning, mathematics and models in action" within this development process or how such innovations are practically managed and coordinated within industrial settings (Vinck 2014: b). Although "prescriptive […] management and methodology studies with examples of good practice and approaches to implement" abound, the models commonly presented by these studies are mostly applicable to idealized objectives, and "what they say about how to proceed hardly tells us anything about how things actually work" (Vinck 2009b: 7). A smaller field of *science and technology studies* (STS) attempts to address this paucity. Among others, Legardeur et al. (2010) show that successful industrial innovations are closely tied to engineers' practical knowledge of such workings, and Mer (2009) demonstrates how the working practices of engineers generate controversies which expand or impede possibilities of action. Nevertheless, these and similar findings from the STS community (see Chapter 2) remain on the periphery of innovation scholarship. Nevertheless, conceptualizations and theoretically substantiated understanding of these workings, which would allow this industrial knowledge to be made visible, manifest itself and become the subject of reflection and learning, are generally absent within the widespread and mostly prescriptive field of innovation management scholarship. Within this body of literature, the *intricacies* of managing industrial technology development are hardly addressed and deserve scrutiny.

Before expanding upon possible STS alternatives and supplements to the widespread and prescriptive approaches for managing technology development in industrial organizations (see Chapter 2), some concepts representative of the outlooks driving these approaches ought to be considered. My purpose is not to disparage these concepts, which in their limited and often mechanistic fashion do provide industrial practitioners with generalizable and easily communicable conceptualizations for considering what innovation is and how it is accomplished (see Bates 2020b). Rather, this enumeration aims to position the intentions of this dissertation within the predominant mindset shaping industrial innovation management scholarship.

1.2.1. CONCEPTS OF INNOVATION

'Innovation', broadly defined as generating and implementing novel ideas, concepts or technologies into new or existing products and processes, is of vital importance for the prosperity of a company (Andreasen et al. 2015; Conway and Steward 2009). Despite this importance, the ways by which innovation is achieved are not fully understood and remain contested (ibid). Conway and Steward (ibid: 2) characterize innovation as "the management of a diversity of often-contradictory practices and goals", where "the management of innovation can be seen as the capability to handle such tensions creatively". In what follows, emphasis is given to what the innovation management literature emphasizes when it comes to handling this diversity of contradictory practices and goals. Reflections regarding the concepts' possibilities and limitations within these contexts, take root in my own 15 years of practical experience leading technology development in industry.

Though innovation management literature is diverse in scope, there is a prevailing macro-perspective – emphasizing 'process models' and 'frameworks', 'strategies' and 'countermeasures' to help industrial top leadership define and achieve 'successful innovation'. In their comprehensive review of process models, Verworn and Herstatt (2002) note that the 'phased stage-gate-process' proposed by Cooper is the most widespread in English and German language academic literature. In his later work, Cooper presents Stage-Gate® as a blueprint for managing both Technology Development (2006) and New Product Development (2008). As such, Stage-Gate® visualizes the innovation process as a series of cross-functional stages, defined as "a set of required or recommended best-practice activities needed to progress the project to the next gate or decision point" (Cooper 2008: 214). Variations of Stage-Gate® are ubiquitous in industrial firms, including Danfoss Power Solutions (DPS), and although these process models often exclude the practices of the individuals tasked with the development of new products or technologies, they have been shown effective in structuring a formalized process from which diverse actors can centrally align distributed actions and expectations. Jensen et al. (2018) propose that the dominant perspective built into such process models is one of management control, focusing more on selecting and (de-)accelerating ideas than on how innovations are encouraged.

Innovation management scholarship is rich with examples for how interorganizational relationships and processes can be dimensioned, so 'successful innovations' might be achieved. Still, aspects of how technology managers and engineers practically enact these relationships and processes, as they lead or develop technology in industrial contexts, are rarely considered. Much of this scholarship strives to define specific idealized roles for actors. Yet the performance of actors within these roles, the interactions of actors with the material contents of innovation (e.g. standards, prototypes, production-processes or even the frameworks presented in the literature) and how these contents are negotiated across often-contradictory practices and goals, are often ignored. For instance, to navigate 'the Valley of Death' between research and 'New Product Development' (NPD), Markham et al. (2010) consider the preparation of ideas for commercial development as dependent on organization-wide variables that can be addressed through a specific distribution of roles (i.e. 'Champions', 'Sponsors' and 'Gatekeepers'). While they do define what these roles are intended to accomplish, Markham et al. provide little assistance in how to achieve success from within these roles, or how these roles are shaped or negated in interactions with the technology being matured. According to Markham et al., their analogy intends to move an organization's focus to precisely that area of development falling between technology research and NPD. To this end, they pose the question as to, "whether applying standard NPD stages and gates [á la Cooper] directly to emerging research is the optimal approach" (ibid: 403). Still, the alternative presented by Markham et al. is an equally linear perception of the transition from invention to commercialization. To accommodate the transition from research to NPD, they propose replacing sequential 'stages and gates' with a series of sequential 'actions' divided between three 'informal' (albeit well- defined) roles until a 'transfer' to NPD can finally be accomplished. Markham et al. are not alone in considering the transition from invention to commercialization as a specialized area of innovation rapt with challenges. Verworn et al. (2008) present how early reductions of market and technical uncertainty, coupled with initial pre-planning exercises, can positively impact NPD. Verworn et al. provide a clear framework encompassing statistical measures from which upper-level decisions regarding the scope of an NDP can be made – prior to beginning such projects. Still their framework does not consider how to handle future challenges associated with validating a technology's functionality and reliability towards the demarcations their statistical measures provide. Both Markham et al. and Verworn et al. propose ways to improve the success of an invention as it moves toward a commercialization process in which a systematic and formalized processes will pace the development process. Within innovation management literature, the area of development wherein these types of preliminary activities occur is often referred to as the 'Front End of Innovation' (FEI, see Bonner et al., 2002; Herstatt et al., 2004; Reid and de Brentani, 2004). Much of this literature incorporates, or responds to, the work of Koen et al. (2001), who define FEI as the area where issues and ideas are fostered before the start of the formal project development phase (Artto et al. 2011: 408).

In their widely cited article, Koen et al. (2001) demonstrate how five different components of their 'New Concept Development Model' (Opportunity Identification, Opportunity Analysis, Idea Genesis, Idea Selection, and Concept and Technology Development) 'iterate' and 'flow' as crucial elements for navigating FEI. Furthermore, Koen et al. argue that proficiency in the 'fluid' aspects of FEI are a prerequisite for successfully completing "the sequential, well-structured, chronologically-ordered steps" (ibid: 51) of the 'New Product and Process Development' (i.e. Stage-Gate®) process into which FEI are intended to feed. While their proposition "that ideas are expected to flow, circulate and iterate between and among all the five elements, in any order or combination, and may use one or more elements more than once" (ibid: 48-49) resonates with both my own experience with technology development in industry and earlier findings by van de Ven at al. (1999), the role of technology, as part and parcel of the structural context of the development process, falls outside the scope of their article. Moreover, the possible means by which any necessary objects included in the Front End of Innovation (e.g. analytical-tools, process models, prototypes and standards) can be situated and utilized within 'Concept and Technology Development' are not considered. While Koen et al. do characterize sub-processes by which innovation can be managed, their focus is on different classes or types of processes and not on the novel or material contents of these processes. As such, their FEI notion overlooks the technicalities of how transitions from Concept and Technology Development to New Product and Process Development (á la Cooper) are practically handled. Integral aspects of the development process are ignored.

Other innovation management scholars focus on how integral aspects of FEI are, or should be, defined. In a longitudinal work spanning four European firms, Frishammar et al. (2013) identify the 'key dimensions of a process definition', that they might conceptualize the 'process equivalent' of a product definition. This endeavor builds on a previous qualitative analysis conducted by Florén and Frishammar (2012: 1), who present 'corroborated product definitions' – definitions which "have been exposed to various forms of tests, analyses, and criticism and have withstood them" – as the final stage of their "Comprehensive Framework of the Front End of New Product Development". This framework understands the Front End "as comprising three core activities: idea/concept development, idea/concept alignment, and idea/concept legitimization" (ibid). Here, the 'idea/concept' (I/C) notion intends to capture how "ideas are gradually transformed into concepts, before materializing into product definitions" (ibid: 38). As such, I/C is presented as the 'key input element' from which corroborated product definitions spring. Like other concepts already considered, 'corroborated product definitions' are presented at an organizational level, as objects serving the overarching organization wherein the translation from idea to product occurs. However, aside from their point that more well-defined and tested corroborated product definitions are more likely to travel further without re-definition, they do not consider how stable product definitions can expand or impede future decision-making possibilities. Moreover, they assume that thoroughly understood customer needs (ibid: 26) will remain stable over the entire course of development, which is a very linear perception of the transition from invention to commercialization. While propositions such as "managers need to ensure that a new idea/concept is screened in terms of its viability as a business proposition, as well as on the feasibility dimension" (ibid: 35) ring true, Florén and Frishammar provide little guidance for how these and similar 'Key Managerial Countermeasures' for handling 'Common Pitfalls' be executed in practice. How corroborated product definitions are utilized and transformed in interaction with the managers and engineers tasked with validating the functionality and reliability of a new technology is unaddressed. Finally, the diversity and magnitude of the other objects that are inevitably incorporated into the development process and through which corroborated product definitions may be (de)stabilized, or how these objects might affect problematizations concerning the suitability of the technology for product specific applications, are not considered. Florén and Frishammar overlook how a product's design and market-specification are reciprocally shaped.

Drawing from an engineering design tradition, Andreasen et al. (2015) advance several methods for forward-looking conceptualization, proposing that thorough preparation will inevitably contribute to the success of a new idea or concept. To this end, they submit the 'Encapsulation Design Model' as a stepping stone methodology characterizing different types of information flow (or exchanges), where "stepping stones supply a map, but not the exact route or decisions to take" (ibid: 111). While Andreasen et al. do acknowledge the transition from technology to product development as an iterative and conflicting process, ways by which the competing problematizations shaping these transitions can be addressed are not included within their methodology.

The iterative and conflicting nature of innovation is otherwise well-documented, particularly by scholars from the Minnesota Innovation Research Program (MIRP) who, have since the 1980's, made significant contributions to the innovation management field (Garud et al. 2011, 2013; van de Ven 1986, 2016; van de Ven et al. 1989, 1999; van de Ven and Garud 1989). In longitudinal studies spanning diverse organizational settings, Van de Ven et al. (1999) identify twelve "common patterns observed during the initiation, development and implementation of a wide variety of innovations" (ibid: 64). Drawing on extensive empirical material, they model relational parameters including events, actions, leadership-roles/relationships/behaviours, and outcomes, to firmly establish 'the innovation journey' as process-theory describing a 'nonlinear cycle of convergent and divergent behaviours'. In more recent work, a few MIRP scholars have expounded these findings to include considerations of 'relational complexity' (Garud et al. 2011, 2013) which draw on notions of 'objects' (Star and Griesemer 1989), 'agency', 'association' and 'concern' (Callon 1986; Latour 1987, 2004, 2005) from STS scholarship (see Chapter 2). This work addresses the sociotechnical aspects and competing problematizations shaping transitions from invention to commercialization more intrinsically than much of the innovation management research already considered. Still, MIRP scholarship remains orientated towards industrial top-leadership and the complex organizational structures and relationships for which these leaders are responsible. Although MIRP scholars acknowledge "that different organizational practices may support or thwart specific agentic possibilities" (ibid), and that objects perform to "connect different relevant social groups whose enrollment is required for the innovation to succeed" (Garud et al. 2013: 785) they provide little guidance for the technology managers and engineers tasked with navigating an 'innovation journey' outside of their control – leaving it to the practitioners themselves, to "explore and experiment with arrangements that harness complexity as a generative force" (ibid: 803).

As this brief enumeration illustrates, the practical means by which actors and their objects are reciprocally positioned, as "the design and implementation of technology are patterned by a range of 'social' and 'economic' factors as well as narrowly 'technical' considerations" (Williams and Edge 1996: 865), are often overlooked in the scholarship considered here. This is also true in the broader field of *management science*, which is often more interested in developing management tools than in studying how these tools perform (Callon 2002). The following subsection describes how this dissertation intends to address that gap.

1.3. RESEARCH QUESTION AND ITS KEY DIMENSIONS

Managing technology development in industry is a complex process, requiring abilities to coordinate efforts across specialized disciplines and knowledge domains, across diverse actors with potentially diverging interests and sometimes conflicting perspectives on how development is defined and accounted for. The complexities of this endeavor include the circulation of a variety of artefacts (including calculative tools, engineering models, development platforms and IT based simulation tools) across multiple actors, concerns and design practices (see Blanco, 2009; Legardeur et al. 2010; Ravaille and Vinck, 2009). Still, the 'practices of the processes' by which these artefacts are circulated are often overlooked (Clausen and Yoshinaka 2009). Moreover, scholars investigating these *practices* in industry are mostly on the periphery of the *processes* – observing, interviewing or intervening (sometimes through the proxy of students) with limited direct contributions to, or tangible experiences with, the work arrangements upon which industries are organized and subsist. However interesting or potentially useful this scholarship might be for industrial practitioners; the fact remains that the intentions of these scholars (or students), how their performance is measured, and their possibilities for action are inherently different than those of the *employees* with whom they interact in industrial cases. This is not always explicitly deliberated and the presumed *actionability* of scholarly findings within these industrial settings and their realms of possibility is often taken for granted. Despite "a venerable tradition" of 'practitioner-analysts' in engineering studies and science and technology studies[4], "where such scholars have drawn on their technical expertise in developing STS arguments", there are only limited works "where the practitioner-analyst remains a practitioner and puts their own individual practice into the vocabulary of the analyst" (Mody 2020: 2). This peripheral involvement in engineering practice could account for why much of what engineers do in industrial settings, and perhaps more importantly *how* they do it, remains a mystery (Vinck 2014: b).

To address these paucities, this dissertation draws from auto-ethnographic studies across different industrial settings to ask: **How can staging with objects contribute to managing technological innovation across specialized knowledge networks?**

The notion of staging with objects is rooted in Clausen and Yoshinaka's 'staging' notion (2005, 2007, 2009, 2020) and scholarship employing this notion within and for industrial practice. Although conceptualizations of staging and objects are more thoroughly unfolded in Chapter 2, the importance and relevance of the notions to the intentions of the dissertation are briefly introduced here.

According to Andreasen et al. (2015: 71), staging is a 'multidimensional' endeavor, where actors are empowered to perform within a process of establishing and fitting a team and its *development space*, according to specific matters at hand. This notion of 'space' circumscribes the limits and possibilities of how diverse actors work, know, and operate towards common ends, often through distributed means (Clausen and Yoshinaka 2007). Andreasen et al. (2015: 78) suggest that such processes make it possible to incorporate the diverse knowledge of a multiplicity of actors into a cohesive whole, and summarize this staging process as incorporating the following tasks (2015: 78):

- Identify and coordinate actors with different knowledge based on their perspectives, ideas, and innovative contributions

[4] Mody names Vincenti (1990) as an example, but I would also include the scholars, Blanco, Clausen, Legardeur, Ravaille, Vinck and Yoshinaka – all of whom have engineering backgrounds and analyze its practice – as 'practitioner-analysts'.

- Motivate actors to be ‘translators’ so that relevant contributions and knowledge are brought into the space
- Balance task composition to take advantage of both detail-oriented and broadly skilled actors
- Monitor, analyze, reflect on, and improve coordination in the space to increase performance.

In addition to the *staging of actors*, Andreasen et al. (2015: 89) also consider the *staging of objects* – stressing the importance of objects being understandable across multiple parties without any single party needing to share or communicate their individual understandings with other parties. This is an interpretation of the *boundary object* notion described in Chapter 2. But more importantly it demonstrates how objects perform to engender work arrangements across other objects and communities. An intricate example of this engendering process is how the geometric dimensions, sampling rate and pressure limitations of a transducer will alter the possibilities for validating the torque limitations of a hydraulic motor’s output-shaft in situ experiments. A simpler example is that the combine harvester into which this hydraulic motor is assembled will require diesel fuel, air in the tires and a driver to complete the test. Such examples exemplify technology development practice as a hodgepodge of objects and actors positioned to perform coordinative action across a diversity of specialized networks. These networks can include industrial functions like Production, Quality, R&D, Sales or Top Management with their own diverse stakeholders, usually the managers of these networks, and mandates to define development processes. But these networks can also include technicians or specialists, who may possess necessary knowledge and skills but lack authority to define strategies and may struggle to articulate their own technical or personal interests. Interactions between these networks are often a product of, and sometimes limited to, the objects they exchange; be these budgets, specifications, machined parts or test results. From an industrial perspective, increased understanding of *how* these objects are selected and positioned to achieve specific objectives (i.e. *staged*) is both a relevant and potentially lucrative endeavor. For those seeking to improve management practices and how these practices pertain to technological innovation across specialized knowledge networks, *objects* provide a tangible path for connecting these networks. But perhaps more importantly, objects also carry the *objectives* of their architects and provide visible manifestations of the success or failures of these objectives (see below). This is the simplest explanation for my motivation to understand the intricacies of interaction between actors and objects, and the mechanisms by which these interactions unfold in processes of technology development. But this dissertation intends to do more than *just* understand these intricacies. It also intends to leverage this understanding to improve industrial practice. It is therefore important that the dissertation’s findings are also *implementable* within the sites and working arrangements it considers.

Although yet another mechanistic approach to technology development lies outside the desires of the host company – "the last thing the division needs is another process model"[5] – the development of a methodological framework that supports technology development *within* the established working arrangements of the company is also a principle motivation behind the company's partnering with my PhD research. To better inform the development of this methodological framework three key dimensions of the research question have been formulated. These are informed by the work of Akrich et al. (2002a, 2002b), where *innovation* can be viewed as a process of stabilizing networks across a diversity of human and non-human actors and stabilizing is viewed as a 'translation of interests' (see also Callon 1984) which can be accomplished through:

1. **Facilitating engagement across specialized networks**
2. **Fostering common points of reference and alignment of interests across diverse stakeholders, and**
3. **Helping actors to articulate and mobilize resources within their organizations.**

Although studied in the context of two specific technology development projects, these dimensions they address key aspects of technology development and are likely to have relevance for technology managers and engineers employed in other industrial settings. Their relevance, as I hope to demonstrate, lies in how they can assist technology managers and engineers in real-time reflections about how objects are, or could be, circulated and manipulated. But I also hope to show that these dimensions can serve as *sensemaking* devices which help practitioners in understanding the performance of their objects in hindsight.

These dimensions are further elaborated in the discussions of Chapter 4, briefly considered in the theoretical concepts presented in Chapter 2 and guide the development of the methodological framework of Chapter 5. For purposes of clarity, the practical implications of the three dimensions are briefly addressed here.

1.3.1. TOWARDS FACILITATING ENGAGEMENT ACROSS SPECIALIZED NETWORKS

Facilitating engagement across networks is a critical part of mobilizing ideas and visions into realizations, but it can be an arduous process and success is not always a given (Clausen and Yoshinaka 2009). At the boundaries of specialized networks, technology managers and engineers are tasked with achieving *irregular* (i.e. innovative) ends through *regular* means – be these structured efforts to accommodate industrywide standards and local NPD process models, or less structured efforts to

[5] From a conversation with a BU Engineering Director on 14 May 2018.

develop novel technologies with and towards established manufacturing, quality and sales infrastructures. According to Jensen et al. (2018), facilitating engagement across specialized networks is dependent on several factors. These include abilities to create and maintain alliances across organizational boundaries, the enrolment of decision-makers and being able to create buy-in from development processes downstream (ibid: 18). Moreover, the processes of engagement through which these actions are made possible are often spread across several threads simultaneously, with their own, often unspoken, intentions. This can make the ways by which engagement is facilitated difficult to follow.

Because objects constitute and trace marks of their authors and their relations, they can reveal something about the intentions and conditions of their migration between specialized networks (Vinck 2012) and how engagement is fostered across these networks. For the sake of argument, assume the *design* of a component specification in R&D is guided by its interactions with other components. Still, and regardless of these intentions at its point of departure, the specification will necessarily be re-interpreted as it moves across the other functions. Although Production will not intentionally undermine the goals of R&D, *manufacturing* the component according to the specification requires that Production (re)interprets the specification in the light of processual necessities associated with factory equipment. These processes will then be considered again, and possibly revised, according to the capabilities of the Quality department to *control* the finished parts on their measurement equipment.

While the motivations shaping the industrial functions will differ across contexts, they must all converge if the component is to be *designed, manufactured* and *controlled* across the cooperating networks (R&D, Production and Quality, respectively). *Objects*, like the component specification above, can thereby provide a means of identifying and analyzing the common structural elements that hold these networks together (Vinck 2012; 2014). Following the ways by which these objects are positioned to *facilitate engagement* across specialized networks, in the face of dynamic, diverging or outright conflicting goals, can thus reveal how the development processes these objects intend to serve are opened or constrained, according to the centralized priorities that are reciprocally shaping distributed work arrangements (see Clausen and Yoshinaka 2009; Vinck 2011, 2012, 2014; Yoshinaka and Clausen 2020, forthcoming).

1.3.2. TOWARDS FOSTERING COMMON POINTS OF REFERENCE AND ALIGNMENT OF INTERESTS ACROSS DIVERSE STAKEHOLDERS

How common points of reference are established across a variety of interests is closely associated with how engagement within a development space is facilitated. Moreover, forms of engagement that are ultimately achieved across specialized networks (however temporarily) must be maintained – often through cross-functional ‘mandates’ and usually in association with parameters that are not necessarily fully defined or considered. Bowker and Star (1996) posit that common points of reference (or what they more specifically term ‘standards and classifications’) are ubiquitous and that how these are aligned across the interests of diverse stakeholders can be viewed as an ongoing process of negotiation. This also rings true for the processes of technology development considered here. Consider the following quote from a BU Engineering Director at the host company.

> To be successful, Engineering needs to understand how to achieve our goals. […] This includes developing small-scale strategies within a mandate. […] But defining and achieving these outputs requires alliances outside of our small teams, as well as recognition from other, sometimes more powerful, networks within the organization [… so that] our actions and communications are relevant for one another and we can stand shoulder-to-shoulder in a fellowship and not as individuals with conflicting expectations or, even worse, conflicting deliverables.[6]

Achieving these ‘fellowships’ requires that stakeholders concurrently adapt objects and work arrangements to the local contexts, constraints and exigencies of the parties employing them, while *also* retaining common identities across the sites into which they are positioned (Star and Griesemer 1989; Vinck 2011). Such ‘infrastructures’ (Bowker and Star 1999; Star 2010) can be specified by the stakeholders themselves, for example the production of prototypes, test-specifications or methods of analyses through which engineers in an R&D department intend to mature an invention’s functionality and reliability according to predetermined milestones. But these infrastructures also include objects and processes on the outskirts, or fully outside, of a stakeholder’s direct mandate, including customer architectures towards which prototypes are being matured, test-rigs to which test-specifications and methods of analyses are directed, or the company sanctioned process models and decision-making tools associated with milestones. Common points of reference and alignment of interests enable stakeholders to define and prioritize these complex infrastructures of objects and work arrangements. Without them, notions of *what* is relevant and *how* this relevance can be maintained (what Latour *calls matters of concern*, see Chapter 2) become difficult – if not impossible.

1.3.3. TOWARDS HELPING ACTORS TO ARTICULATE AND MOBILIZE RESOURCES WITHIN THEIR ORGANIZATIONS

The importance of articulating and mobilizing resources in processes of innovation is certainly acknowledged within scholarship focused on staging and objects (see Clausen and Yoshinaka 2009; Vinck 2012, 2014; Yoshinaka and Clausen 2020, forthcoming). Nevertheless, longitudinal studies regarding how industrial

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[6] Translated from Danish and edited for brevity and clarity, from a conversation on 14 December 2017.

practitioners stage such objects to articulate and mobilize resources are limited. Moreover, these scattered findings are to a large degree anecdotal – stemming from researchers who were not necessarily embedded within the locally situated understanding of the objects they observe, nor reciprocally involved in manipulating these objects towards innovative ends. Relevant scholarship from the hands of actors integral to the work by which industrial organizations subsist is sparse (Mody 2020: 2).[7]

For those of us employed in industry, this is especially disconcerting. If as, Clausen and Yoshinaka propose, "[k]nowledges are configured, stabilised, and facilitated (explicitly or otherwise) to give particular meaning, through particular heterogeneous enactments and *collective mobilisation of resources*" (2009: 4, my italics), then technology managers and engineers must develop and hone their abilities to collectively understand and articulate *when*, *why* and *which* objects and actors are necessary for achieving specific and distributed objectives. To these ends, I exploit Clausen and Yoshinaka's staging notion to reflect on my own practice, combining insights as a technology manager and engineer working in industrial settings with an academic analytic perspective. This is accomplished via the industrial cases presented in the following section.

1.4. INDUSTRIAL CASES OF TECHNOLOGY DEVELOPMENT

My PhD research was performed as an extension to my day-job as a *technology manager* – with responsibility for technology development spanning four factories (China, Denmark, Poland and USA.) and two R&D centers (China and Denmark). In this respect, *delimiting* possible sources of empirical material proved far more challenging than *finding* these sources. My selection of industrial cases stems from two principle considerations: 1) my role as 'auto-ethnographer' (cf. Hayano 1979) and; 2) endeavors to accommodate the 'Biographies of Artifacts and Practices' (BOAP) framework advocated by Hyysalo et al. (2019). Although auto-ethnography and BOAP are both elaborated in the methodological considerations of Chapter 3, they are briefly introduced here to help contextualize the selection of industrial cases.

To better understand what 'auto-ethnography' is, let us start with a definition of 'ethnography'. Like *innovation*, the term ethnography is contested. As Ingold says, "Ethnography has become a term so overused, both in anthropology and in contingent disciplines, that it has lost much of its meaning"(2014: 383). For

[7] This has not always been the case. From the late 1970's, Lucy Suchman, Randall Trigg and Jeanette Blomberg all "explore[d] relations between everyday practices, design and use" (Suchman et al. 1999: 392) via their employment at the Palo Alto Research Center. and drawing from their own intimate involvement in developing and optimizing new products and technologies. This intimacy also extended to taking multiple patents on XEROX's behalf (Trigg et al. 1992; Mahoney et al. 1999).

purposes of precision, I draw on Ingold's concise definition of ethnography: "Quite literally, it means *writing about the people*" (ibid: 385). In his groundbreaking article, Hayano (1979: 99) defined the "entire scope of issues" related to auto-ethnography as being concerned with three main points: "(1) how anthropologists conduct and write ethnographies of their "own people"; (2) the problems of methodology and theory associated with this approach; and (3) whether anthropology can profit from these exercises".

Hayano developed these points through his own auto-ethnographic research, leveraging his 10-years' experience as a regular poker player in the legal cardrooms of California and Nevada to pursue *anthropological* research on gambling (Hayano 1977, 1900, 1982). Although I am not an anthropologist, I do leverage 15-years of experience as a technology manager and engineer towards social science research seems to resonate with Hayano's research intentions, which includes, "the works of other social scientists who have done intensive participant-observation research in natural field settings" as relevant for the *scope of issues* through which he defines auto-ethnographic practice (1979: 99). To exploit this relevance, I replace 'anthropologists' with 'technology managers and engineers' when considering Hayano's first point, and 'anthropology' with 'technology development' when considering his third point. My intention is not to take on the mantle of 'anthropologist' – a craft in which I am not formally trained. Rather, I exploit a tool from anthropology in which I am schooled (i.e. *auto-ethnography*) to research the craft of 'technology development' in which I am skilled. It is uncertain if an engineer *unschooled* in auto-ethnography could master this method. Still, I submit that the written and representational work of engineering practice enabled my auto-ethnographic efforts. Reflections on the success of this endeavor fall outside the scope of this subsection and are detailed in Chapter 6 where I reflect on Hayano's statement that "auto-ethnography is not a specific research technique, method, or theory, [rather] it colors all three as they are employed in fieldwork" (1979: 99).

Here it is important to note, that while my technology management position within the host company did provide immediate and widespread access to diverse sites of technology development, specific cases of study through which my research question and sub-questions could be investigated still needed to be identified and selected. According to Czarniawska (2014: 22), "the most common error [in pursuing case studies] is definitely that of mistaking the site for the phenomenon under study". I find this proposition particularly relevant for auto-ethnographic research where the selection of cases must support a research process which necessarily oscillates between *observing* and *acting* at a higher frequency than other types of fieldwork (Adler and Adler 1997; Anderson 2006). "Observers are able to see options – and to distinguish among them. But actors can see options only in the moment of reflection, of observing, of not acting" (Czarniawska 2014: 5). According to Adler and Adler (1997) another primary challenge faced by auto-ethnographers relates to the ways they must re-situate themselves into otherwise familiar settings:

> Instead of having to bring their research self to a setting and carve out a membership role, the reverse occurs. Here we see people familiar with a setting having to create the space and character for their research role to emerge. They must look at the setting through a fresh perspective, to develop relationships with people they did not associate with previously, to change the nature of their preexisting relationships, and to become involved with the setting more broadly (ibid: 70).

These challenges were all considered in the selection of the two cases, which were instigated just before and soon after the official start of the PhD project. Because both cases comprised new technologies for the division, it was reasoned that they could provide unique possibilities for accessing *fresh perspectives* – without necessarily reinventing the *space* or *character* of an existing project. In this way, it was possible to incorporate my new *research role* into the projects as they were being developed and to successfully redefine specific *preexisting relationships.* Reflections on the scope and success of this endeavor are voiced in Chapter 6.

Considering the selection of cases for fieldwork, Czarniawska (2014: 22) asks:

> [I]f cases are sites, what should be done if one site presents an opportunity to study several different phenomena – like most of the sites chosen by ethnologists and anthropologists? Or when a phenomenon occurs at several sites at once […]?

To accommodate these questions, I'm inspired by the 'Biographies of Artifacts and Practices' (BOAP) framework advocated by Hyysalo et al. (2019) - both in my selection and analyses of cases. Arguing for 'multi-site, longitudinal studies' that move beyond unrelated studies of the intricate practices of particular settings, Hyysalo, Pollock and Williams (2019; Williams and Pollock 2012, 2009) propose that an adequate picture of how technology takes shape, requires that *both* the wide range of sites where the technology evolves *and* the connections between these settings be investigated.

The selected cases illustrate different types of industrial technology development. Both cases were led by me over periods exceeding 20 months. The first case addresses a host company devised technology as it is matured through interactions with and towards the mobile hydraulic market. The second case describes an industrial-academic collaboration around a key technology for the mobile hydraulic market – the hydraulic lubricants upon which the industry rests. While differing in scope, both cases are multi-sited. The first case includes interactions between stakeholders from and at different locations. These locations include host company and customer production sites, engineering, sales and patent offices, test-tracks, and diverse measurement and testing laboratories. The second case includes similar interactions and locations – this time distributed across the facilities and personnel of the host company, its academic partners and a university start-up company. To complicate matters further, both cases represent two poles of technology development: a) attempts to move novel (albeit immature) technologies towards commercialization and; b) attempts to move established markets in directions where such technologies can be exploited by their inventors and collaborators. As such, the selected cases represent a complex arrangement of longitudinal, mutually shaping multi-sited phenomena through which technology development practice can be investigated. Before proceeding to describing the cases, I briefly introduce the host company.

1.4.1. THE WORK FUNCTIONS DIVISION OF DANFOSS POWER SOLUTIONS APS

Since its inception in 1933, the family owned, Danish concern Danfoss A/S has placed engineering science at the fore of its endeavours, wrestling with the development of new technologies from patented inventions. As such, Danfoss identifies more as engineering than manufacturing concern (Sønnichsen 2006). This identification is presently visible in the company slogan, 'Engineering Tomorrow', and is elaborated in the following text, included in the concern's annual report (Danfoss A/S 2020: 6) and sanctioned presentations:

> Across the globe, our sustainable, smart technologies power industries and cities, secure a reliable food supply, and create healthier, more comfortable indoor climates. At the same time, we are developing solutions that integrate renewables into tomorrow's smart energy systems, where on- and off-highway machinery, cars and marine vessels are powered by hybrid and electric motors.

Danfoss Power Solutions ApS (DPS) was wrought from the Danfoss purchase of a license agreement to fabricate patented hydraulic technologies from the Char-Lynn Company of Minnesota (Bender 2004). Almost 60 years later, DPS is the largest Danfoss business segment and accounts for approximately 35% of Danfoss total net sales (Danfoss 2020: 25). Providing a complete portfolio of hydraulic solutions for the off-highway mobile industry, DPS consistently claims the first or second global market position, with sales exceeding 2bn Euro/year (ibid: 26).

The two selected cases stem from the Work Functions (WF) division of DPS, where I have been employed since 2005. With annual sales of approximately 500 million Euro, WF employs over 2000 people at eight different factories in seven countries. Of the divisions four *business units*, BU Motor and BU Steering are the largest, consistently achieving number-one global positions in their respective markets, both in product volumes and profitability (Danfoss A/S 2020). The first case takes place in BU Steering, where I have led technology development projects since 2016. The second case takes place in BU Motor, where I have led technology development projects since 2006.

1.4.2. MANAGING THE TRANSLATION FROM CONCEPT TO COMMERCIALIZATION IN THE OFF-HIGHWAY MOBILE HYDRAULIC INDUSTRY

This technology development project (TDP) began in 2015, when a part-time project group in BU Steering at the Work Function (WF) division of Danfoss Power Solutions ApS (DPS), submitted two patent applications (Ennemark et al. 2016a, 2016b) for a novel steering technology that would make full hydraulic steering safe and comfortable at speeds over 50 km/h.

In 2016 WF Senior Management selected the technology for further development and a preliminary TDP Team was tasked with defining a course of action. Over the following months, resources were secured, and a five-member Core Team was constituted. This team included me as acting TDP Manager, a Simulation and System Specialist, a Mechanical Hardware Specialist, a Simulation and Design Specialist and a Senior Design Specialist. Between January 2016 and May 2018 the Core Team submitted nine new patent applications (Arbjerg et al. 2018a, 2018b; Bates et al. 2018a, 2018b, 2018c, 2018d, 2018e, 2018f; Frederiksen et al. 2019), developed and tested multiple prototypes, and devised numerous test-specifications, equation-based dimensioning tools, dynamic simulation models and methods of analyses – all purposed with establishing the functionality and reliability of the technology in off-highway vehicles for the construction, agricultural and material-handling markets in which WF operates. During this time the Core Team also worked closely with WF Sales, organizing and participating in Technology Demonstrations and Workshops with some of the world's largest Original Equipment Manufacturers (OEMs), in Denmark and abroad. From May to September of 2018, I also co-led the transition from Technology Development Project to Product Development Project, where competing problematizations and qualifications concerning the suitability of the technology for product specific applications were negotiated, in planned and preparatory meetings for, and with, WF Senior Management.

This case provided the empirical material for developing one published article, one forthcoming book chapter, one article presently under review, and the methodological framework of Chapter 5. When referencing the papers, page numbers refer to the versions in the Appendix, whose titles and placement are as follows.

- *Engineering Readiness: How the TRL Figure of Merit Coordinates Technology Development* (Bates and Clausen 2020 – see Appendix A)
- *Staging with objects: Translation from Technology to Product Development* (Bates 2020a, forthcoming – see Appendix B)
- *Positioning Patents to Perform Coordinative Action in Industrial Technology Development* (Bates 2020b – see Appendix D)

1.4.3. AN INDUSTRIAL-ACADEMIC COLLABORATION TO COMMERCIALIZE A SUSTAINABLE SUBSTITUTE FOR PETROLEUM-BASED LUBRICANTS

This case follows a collaboration between BU Motor at the Work Function (WF) division of Danfoss Power Solutions ApS (DPS), Luleå University of Technology (LTU) and Sustainalube AB, an LTU spin-off company. The collaboration was instigated at the behest of LTU and led by me.

Since 2005, WF has worked closely with LTU to understand and simulate mechanisms influencing orbital gear-set functionality and reliability. This work includes bespoke kinetic and mechanical simulations, ad hoc optical measurements and analyses of finishing processes, as well as multiple co-authored publications (Furustig et al. 2015a, 2015b, 2016). In December 2017, the Chair Professor for the Faculty of Engineering and Natural Sciences at LTU requested that WF assist LTU and an LTU spinoff company, Sustainalube AB, in benchmarking a 'sustainable' renewable, nontoxic, water-miscible replacement (Björling and Shi 2019; Shi et al. 2013) for ISO 32 Type II Base Oil – the de facto (albeit toxic) standard for off-highway mobile lubricants. Sustainalube had successfully positioned the technology as a substitute for grease and chainsaw-lubricants in forestry, but to break into the exacting mobile hydraulic market, the LTU spin-off needed credible evidence for the functionality and reliability of their lubricant in industry relevant applications.

The collaboration began in May of 2018 and was still in progress at the time of this writing. Activities included numerous workshops and meetings (at DPS in Denmark and LTU in Sweden) to align measurements, industrial tests, tribology experiments and industry wide standards and interpretations of unexpected results with the differing needs and expectations of the supporting organizations. These activities all included complex negotiations around how completed and planned action could be made relevant for the diverse organizational and institutional requirements of the collaborating parties. Additionally, this relevance needed to be maintained and renegotiated in the face of unexpected results. Towards understanding this complexity, I involved Assistant Professor Joakim Juhl (Department of Planning, Sustainable Design and Transition at Aalborg University) in workshops from the start of the collaboration, that we might utilize and expand his 'Innovation Science' concept - a notion denoting a "domain of knowledge production […wherein] academic scientists produce knowledge for commercial ends" (Juhl 2016: 136).

This case provided the empirical material for developing one forthcoming book chapter, a working paper and the methodological framework of Chapter 5. When referencing the papers, page numbers refer to the versions in the Appendix, whose titles and placement are as follows.

- *Staging referential alignment in industrial-academic collaboration* (Bates and Juhl 2020, forthcoming – see Appendix C)

- *Conceptualizing Referential Alignment in Innovation Science* (Juhl and Bates 2020 – see Appendix E)

1.5. SUMMARY OF CHAPTER 1

This chapter presents my motivation for researching how staging with objects can contribute to managing technological innovation across specialized knowledge networks. The chapter also introduces different concepts from innovation management literature, considering how these diverse concepts emulate and resonate with industrial technology development as viewed from my own practice and STS scholarship. The chapter presents the research question, **how staging with objects can contribute to managing technological innovation across specialized knowledge networks** and argues for its specific relevance for three key dimensions of innovation – viewed as a process of 'stabilization' across human and non-human actors – and the 'translation of interests' within this process. The chapter also declares my intention to develop a methodological framework, focusing on how *staging with objects* can supplement these key dimensions: Facilitating engagement across specialized networks; Fostering common points of reference and alignment of interests across diverse stakeholders, and; Helping actors to articulate and mobilize resources within their organizations. Finally, the chapter describes how I selected industrial cases through considerations pertaining to auto-ethnographic research and, to a lesser degree, demands to 'multi-sited, longitudinal' cases from the Biographies of Artifacts and Practices Framework.

The remaining chapters of this dissertation are rooted in the preceding deliberations and are structured as follows.

- Chapter 2 introduces the theory and concepts from STS scholarship through which the empirical material and sociotechnical aspects of technology development are later considered.
- Chapter 3 expounds the methodological considerations upon which this dissertation rests.
- Chapter 4 presents a discussion wherein empirical material from the two cases is analyzed from the perspectives of STS theory presented in Chapter 2, that is in turn structured according to its relevance for the research question and three sub-questions.
- Chapter 5 draws from the preceding chapters to develop and present a methodological framework for managing technology development in industry.
- Chapter 6 includes reflections over the academic novelty and limitations of this dissertation in light of the intentions declared in Chapter 1. It also

considers the limitations and implications of the developed methodical framework for engineering practice.

- Chapter 7 is an appendix of the papers engendered by my PhD research.

2. THEORETICAL BACKGROUND

This chapter focuses on approaches to understanding the challenges of innovation and technology development. Emphasis is given to how insights from *science and technology studies* (STS) can support the practical work of technology managers and engineers employed in industry. These efforts are guided by the research question presented in Chapter 1, which asks **how *staging with objects* can contribute to managing technological innovation across specialized knowledge networks**. Before elaborating on notions of *staging* and *objects*, I introduce the key tenants and sensitizing concepts from STS that shape this dissertation, its analysis and findings. To these ends, the chapter begins with an introduction to sensitizing concepts and key tenets from STS scholarship. Elaborations on *staging* and *objects* are then presented, with outset in the preceding subsections, before the chapter closes with a brief summary.

2.1. RECENT SCHOLARSHIP ADDRESSING THE SOCIOTECHNICAL IN ENGINEERING PRACTICE

There is widespread and recent scholarship which draws from STS theory to describe interdependencies and interwoven relations between the social and material in engineering practice. What these authors share is the proposition that social interactions ought to be viewed as an integral element of engineering practice as opposed to something peripheral to a technical core. Trevelyan (2010) points at 'distributed expertise' as a foundation of engineering practice, arguing that engineering is a process of harnessing the knowledge, experience and skills of many people in order to (re)arrange a variety of components, materials, and abstract data towards specific ends. The work of Vinck (20010, 2011, 2012, 2014; Vinck et al. 1996) is particularly relevant to this dissertation and provides further indications of how the social and technical are intertangled in engineering practices. Drawing on actor network theory and ethnographic studies, Vinck's work points at the key role of objects in engineering and how the ways by which these objects are 'equipped' become central concerns for engineers and technicians tasked with acquiring and disseminating knowledge across the boundaries of organizational responsibilities (2011: 25). Vinck is not alone in considering the role of objects in engineering work. Blanco (2009) investigate the means by which rough sketches made by designers perform to reveal and mediate the design process, to conclude that rough sketches "create conflicts between differing points of view and make cooperation possible" (198-200). In a similar vein, Boujut and Blanco (2003: 2005) highlight "the importance of the material involved in co-operative processes, [to more] specifically […study…] the role of different types of objects as mediators in the building of shared representations". Broberg et al. (2011: 469) identify eight characteristics of boundary objects and their utilization in how "workers and other workplace end-users participate in setting up measures for ergonomics". Hansen and Clausen (2017: 21) view management concepts as 'devices of interessement' implemented towards specific goals of organizational change, to analyze two different industrial settings to conclude that pre-configured interessement devices are “reformed and reconfigured” in their implementation, where these devices also “reform and reconfigure, the networks of socio-technical relations in which they are embedded”. Likewise, Hussenot and Missionier (2010: 269) demonstrate that the “roles and natures of objects evolve over time through controversies and compromises [… where…] the evolution of interactions drives the evolution of the roles and natures of objects […and…] the evolution of objects help[s] the actors to structure their interactions and activities.” Lee and Amjadi (2014) investigate the ‘everyday work’ and troubleshooting practices of engineers in a semiconductor plant, to illustrate how objects *activate* interpretations, *stimulate* collaborative practices, and *spark* experimental activities. Finally, Rau et al. (2012: 209) provide “a comprehensive overview of the interdisciplinary research that explores the use of innovation practices to cross semantic and pragmatic boundaries in innovation projects”, to identify diverse tools and methods and document the “recurring boundary-crossing mechanisms inherent in a multitude of innovation practices”.

These fruitful findings from the frontlines of industry are both inspiring and relevant to the intentions of this dissertation. Still, the foci of these studies are mostly concerned with the interplay of objects in shaping *design contexts* or, as in the case of Hussenot and Missionier (2010: 270), developing frameworks “to follow and study the evolution of objects in organizational processes”. STS research with an *explicit* focus on how objects are intentionally situated to *coordinate* or *manage* transitions from invention to commercialization in industrial contexts is rare. Exceptions include: Legardeur et al. (2010), who follow how actors and their objects interact in the process of creating a ‘system of alliance’ in the early phases of an unfulfilled industrial innovation; Webster and Gardner (2019) who delve into how the ‘Technology Readiness Level’ (TRL) *figure of merit*[8] performs to align technology and institutional readiness in the adoption of innovation, and; Gish and Clausen (2013) who interview stakeholders in an industrial firm and detail sociotechnical notions of ‘framing’ in order to analyze and understand the complexities of moving a product concept towards commercialization.

As I intend to demonstrate, my PhD research aligns with established STS theory and practice. Anthropologists like Suchman, Trigg and Blomberg who have conducted research from embedded roles within industrial settings (see Suchman et al. 1999) have certainly inspired my *auto-ethnographic* approach. Still, there are principle points of divergence between our *embeddedness* that set our work apart. In counterpoint to my experience as an *industrial practitioner*, which I leveraged to foster and enable a social science research agenda, for Suchman, Trigg and Blomberg their research was motivated by *anthropological research agendas*, which drove

[8] In the engineering and natural sciences, a figure of merit, “usually presents itself as a single number that reflects the status or the performance of any particular system under particular specified conditions” (Borg et al. 2012: 1).

them towards (and continue to enable) their industrial practice. As such, this dissertation aims to provide new empirical insight into how technology development is practiced and coordinated by, across, and perhaps most importantly *for* industrial practitioners. To my knowledge, this is the first STS based dissertation to be completed by a researcher as an extension to their 'day job' as technology manager or engineer. Here, I attempt to *theorize* accounts of my industrial *practice* in ways that resonate with other STS researchers occupied in academia while ensuring that these accounts remain recognizable for engineering colleagues employed in industry and (ideally) support their practice. This requires balancing between the different rules for accountability and performance criteria separating these worlds – a subject to which I return in the reflections of Chapter 6.

The responsibilities of this *day job* include defining and executing the 'technology roadmap', in a business unit with sales exceeding 250 million Euro/year, across R&D, test and production facilities in China, Denmark, Poland and USA (Danfoss A/S 2020b). Although these responsibilities provide unequivocal empirical access to the daily workings and challenges of managing technology development in an industrial organization, it became clear from the start of the PhD that accommodating the duality of my practitioner-analyst role would require theoretical concepts with practical relevance. To these ends, theoretical concepts where selected according to their supposed abilities to connect exigencies of the technical and social in engineering practices, with a focus on how these concepts could illuminate coordinative efforts. Meeting the responsibilities of my technology manager position entailed spending significantly more time with colleagues engaged in industrial practice (scholars of engineering and natural sciences employed at universities supporting the off-road mobile hydraulic industry included herein), than with academics of the social sciences engaged with theoretical aspects of innovation and its management. Rather than viewing this as problematic for my PhD research, I see this as endemic to actual processes of transitioning from invention to commercialization in industry, where scholars occupied with technology development or innovation management are only rarely and peripherally included in these endeavors. During my PhD, such associations were fostered through *ad hoc* student internships and projects (including cases within DPS which I provided for other PhDs), or by relations established via company endowments for university departments or centers, and space leased at 'innovation parks' connected to a university campus[9] – if at all. I have therefore only included concepts for theoretical reflection which: a) were introduced, by me, into 'on-the fly' discussions with engineering and management *colleagues* to support impromptu reflections on the nature of the micro-processes in which we found ourselves, and; b) resonated with my colleagues insofar as these concepts seemed to

[9] In addition to establishing the Mads Clausen Institute at the University of Southern Denmark, Danfoss maintains 'collaborative spaces' at the Science Park at the Technical University of Denmark (DTU) and the Cambridge Innovation Center at the Massachusetts Institute of Technology (MIT).

expand, rather than impede, our dialogues. Concepts meeting both criteria are explicated in the following subsection.

2.2. SENSITIZING CONCEPTS AND KEY TENETS FROM STS

This dissertation aims to illuminate how technology development is practiced and coordinated by, for and across industrial practitioners, with intentions to improve industrial efficacies in transitioning from processes of invention to processes of commercialization. To support these endeavors, this subsection identifies a variety of *sensitizing concepts* and key tenets from STS scholarship. Bowen (2006: 2-3) defines ‘sensitizing concepts’ as:

> [I]nterpretive devices serving as a starting point for a qualitative study […which] draw attention to important features of social interaction and provide guidelines for research in specific settings [… or are used] simply to lay the foundation for the analysis of research data.

To help identify sensitizing concepts and key tenets from STS, I start with an auxiliary understanding of the field of scholarship from where these concepts arose. This understanding is rooted in a pivotal article by Williams and Edge (1996: 866) map the ‘Social Shaping of Technology’ (SST) domain as a 'broad church', denote its different strands and delineate the relationships between them:

> We therefore adopt a very broad definition of SST, without implying a particular consensual 'orthodoxy', clear boundaries or claims of ownership to the field. As we hope to show, much of the strength in this area lies in the very diversity of work which it encompasses (ibid).

Continuing in this vein, Williams and Edges propose that a diversity of SST scholars are united through their insistence that the 'black-box' of technology must be opened in ways that “allow the socio-economic patterns embedded in both the content of technologies and the processes of innovation to be exposed and analysed” (ibid). Despite this shared perception, it is crucial to note that not *everyone* included in the ‘SST domain’ defined by Williams and Edge (and later by Russel and Williams 2002) would accept this positioning. Among these scholars, the work of Callon, Latour, and Law reject all *a priori* distinctions between the social and the technical (a distinction which the name ‘social shaping of technology’ implies). Perhaps a more fitting, and certainly less contentious, name for this ‘broad church’ is *science and technology studies* (STS), which includes SST and denotes a wide field of scholarship that most, if not all, of this chapter’s theorists would consider themselves a part. Within this broad church of STS, ‘Actor-network Theory’ (ANT), not only provided early and influential approaches for following the actions and strategies of actors through their network building endeavors (Russel and Williams 2002) but was also the source of the key tenets discussed here. These tenets were initially defined by Callon, Latour and Law and took root in a deceivingly simple question posed by Callon *circa* 1980:

"[H]ow can we describe socially and materially heterogeneous systems in all their fragility and obduracy?" (in Law 2009: 143).

Law (ibid: 144) suggests the concept of 'translation' as a possible starting point: "To translate is to make two words equivalent. But since no two words are equivalent, translation also implies betrayal: *traduction*, *trahison*. So translation is both about making equivalent, and about shifting". In his "exemplary" articulation of such movements (ibid) Callon (1984) posits four moments and an obligatory passage point as inherent to the process of defining, organizing and maintaining *any* network – regardless of its ostensible fragility or robustness. According to Law (2009) this seminal paper "is also notorious because Callon analyzes people and scallops in the same terms. His "generalized symmetry" applies not, as in the sociology of science, to truth and falsity, to epistemology, but to ontology, to the different kinds of actors in the world" (ibid: 144-145). As Law points out, this was a radical extension of the then prevailing 'methodological dictum' stemming from Kuhn's *The Structure of Scientific Revolutions* (1962) – or what Bloor (1976) later termed "the 'principle of symmetry': true and false knowledge, it was said, need to be explained in the same terms" (Law 2009: 144).

Callon presents 'problematisation' as the first *moment of translation*. "To problematise is simultaneously to define a series of actors and the obstacles which prevent them from attaining the goals or objectives that have been imputed to them" (Callon 1984: 228). For a problematization to be successful, the *interests* of actors must be piqued. This is easier said than done. Interests can waiver. To stabilize any network, however temporary, an 'Obligatory Passage Point' (OPP) around which the goals of diverse entities can coalesce, must be established. An OPP is not itself a moment of translation, but rather a characteristic of the conditions that define a network – or put simply, the situation that *must* occur for any network to manifest, persist or desist. Only through such conditions can the second moment, 'interessement', come into play. Callon defines *interessement* as "the group of actions by which an entity […] attempts to impose and stabilize the identity of the other actors it defines through its problematization" (ibid: 207). The cumulative result of a successful interessement is the third moment: 'Enrolment'. It is here that entities are locked into specific roles and spokespeople emerge – with mandates defined by and for the devices of interessement and OPP supporting the network. Importantly, Callon reminds us that to speak for others:

> […] is to first silence those in whose name we speak. It is certainly very difficult to silence human beings in a definitive manner but it is more difficult to speak in the name of entities that do not possess an articulate

> language: this supposes the need for continuous adjustments and devices of interessement that are infinitely more sophisticated (1984: 216).[10]

The fourth moment, 'mobilization', can be seen as the *actualization* (however brief) of established mandates. "To mobilize, as the word indicates, is to render entities mobile which were not so beforehand" (ibid). Mobilization is per definition instable. Dynamic entities change and become displaced. New problematizations arise. Consequently, "[t]he choice of each new intermediary, of each new representative must also meet a double requirement: it renders each new displacement easier and it establishes equivalences which result in the designation of [… spokespersons]" (Callon 1984: 218). Returning to Law (2009: 145), "translation is always insecure, a process susceptible to failure. Disorder – or other orders – are only precariously kept at bay".

Law (1987) purports that the means by which this (in)stability is maintained or changed can be viewed through the concept of 'heterogeniety'. To this end, Law considers Portugal's historic domination of the spice trade as a process of 'heterogeneous engineering', made possible by an *emergent phenomenon* (the galley: a conglomerate entity possessing attributes not shared by its individual components). This dissertation contains a variety of such emergent phenomena. For example, the test-setup for validating functionality and reliability of hydraulic lubricants in the paper by Bates and Juhl (2020), or the Technology Readiness Assessment figure of merit considered in the paper by Bates and Clausen (2020). Both examples are elaborated in Chapters 4 and 6, but for now it is sufficient to state that Law's *heterogeneity* provides "a family of methods for associating and channeling other entities and forces, both human and nonhuman" (ibid: 109). Law argues, "that the stability and form of artifacts should be seen as a function of the interaction of heterogeneous elements as these are shaped and assimilated into a network" (ibid: 113). But Law (2002: 136) also warns against viewing these exchanges as a simplified process where "a great designer, a heterogeneous engineer", single-handedly manipulates a diversity of elements:

> "Instead, we need to hold on to the idea that the agent – the 'actor' of the 'actor-network' – is an agent, a center, a planner, a designer, only to the extent that matters are also decentered, unplanned, undesigned. To put it more strongly, we need to recognize that to make a center is to be made by a noncenter, a distribution of the conditions of possibility that is both present and not present" (ibid).

This citation clearly illustrates another key tenant of ANT, the concept of *semiotic relationality*. Be we economists, engineers, lawyers or tradesmen (all of whom were

[10] I return to this citation in Chapter 4. For now, the reader may infer that it encapsulates principle dilemmas for technology managers and engineers negotiating interactions across and with a diversity of objects and networks.

present and accounted for in the industrial cases of this dissertation – see Chapter 4) our *conditions of possibility* are impeded or expanded in tack with the (in)stabilities of the networks of which we are a part, and the fragility and obduracy of the objects and actors at their *(non)centers*.

According to Latour (1987: 243), “the construction of the[se] centres requires elements to be brought in from far away – to allow centres to dominate at a distance – *without* bringing them in for good – to avoid centres being flooded”. Latour defines such ‘centres of calculation’ as allowing diverse elements to be mobilized from a single source. By “bring[ing] together entities from far-reaching horizons and creat[ing] the possibility of making a switch from local, indigenous knowledge to universal knowledge” (Vinck 2010: 235), *centers of calculation* allow “familiar[ity] with things, people and events, which are distant” (Latour 1987: 220).

To demonstrate the workings of such *centers*, consider Latour’s classic example of the Reynolds formula – which also possesses a high degree of relevance to the dissertation’s case on commercializing a sustainable substitute for petroleum-based lubricants (see Bates and Juhl 2020; Juhl and Bates 2020). To illustrate the dynamics of a center, Latour (1987) expounds on the Reynolds formula:

$$R = \frac{SLD}{V}$$

Simply put, the Reynolds formula describes how the turbulence of a medium is proportional to the speed (S), to the length of an obstacle (L) and to the density (D) of the medium, while it is inversely proportional to the viscosity (V) of the medium (ibid: 238). According to Latour, what makes this (and potentially all other equations) powerful, is that it “allows[s] elements to be brought together, mobilised, arrayed and displayed”. Specifically, the Reynolds formula makes it possible to label and compare all possible types of turbulence, “whether galaxies in the sky” or “a fast, little creek running against a stone” (ibid). This non-dimensional number thereby allows scientists to both move *between* models of scale and *across* different types of turbulence that are “far away in space and time” (ibid: 239). Even so, the *efficacy* of the number is, and remains, fully dependent upon the networks that support it.

Returning to the intentions of this dissertation, such networks also include hydraulic engineers like myself, who are employed with the design, verification and manufacturing of off-highway mobile vehicles and their components. When validating novel products within this industry, organizations must identify and accommodate mutually acceptable means of analyzing and translating the functionality and reliability of these products into a variety contexts, (for example, national emissions and safety regulations) across a diversity of specialized networks spanning, but not limited to, component and vehicle manufacturers, distribution centers, farmers, mechanics and governmental agencies – as these networks persist or desist, individually or in tandem. Summarizing Latour, the Reynolds number, like *all* centers of calculation, "plays such an important role [only] *because and as long as* the mobilization of these networks is under way" (ibid: 239). When viewing the Reynolds formula as a center of calculation, many of the key tenets of actor-network theory become visible. There is what Law (2009) terms *semiotic relationality* "(it's a network whose elements define and shape one another), *heterogeneity* (there are different kinds of actors, human and otherwise), and *materiality* (stuff is there aplenty, not just 'the social')" (ibid: 146, my italics). But perhaps more importantly, it demonstrates the dogged focus on process and its instability that is necessary for pursuing a research agenda focused on *associations* – where "all elements need to play their part moment by moment or it all comes unstuck" (ibid).

To move attention towards how such associations are manifested and held together, Latour (2005: 114) proposes and formulates 'matters of concern', which he explains as uncertain, disputed, objective, atypical, "and above all, interesting agencies" more readily understood as 'gatherings' than 'objects'. This perception is salient because it provides a means for considering 'multiplicity' as a property of 'facts'. These facts, according to Latour, are not only fabricated, but also exist "in many different shapes and at very different stages of completion" (ibid: 118).

> A matter of concern is what happens to a matter of fact when you add to it its whole scenography, much like you would do by shifting your attention from the stage to the whole machinery of a theatre (Latour 2008: 39).

Empirical examples of this *shift in attention* were readily apparent in this dissertation's fieldwork on moving a novel hydraulic invention towards commercialization (Bates and Clausen 2020; Bates 2020a, forthcoming; Bates 2020b; Chapter 4). Here, the technology development team often oscillated between two poles regarding how to best utilize company sanctioned management tools. At the first pole were negotiations regarding the widespread and accepted ideas on how these standardized and sanctioned tools were intended to document and support decision-making processes concerning the *readiness* of the technology across the organization. At the second pole, were negotiations regarding how the same tools could be situated in new contexts to support more local concerns within the technology development process associated with achieving this *readiness*. This resonates with another observation by Latour (2005: 116) on the characteristics of a matter of concern:

> *It is the thing itself that has been allowed to be deployed as multiple*, and thus allowed to be grasped through different viewpoints, before being possibly unified in some later stage depending on the abilities of the collective to unify them.

In the preceding text, I have attempted to formulate how key tenets from ANT – *matters of concern*, *centers of calculation*, *semiotic relationality*, *heterogeneity*, and *moments of translation* – can supplement the principle enquiry of this dissertation: **How staging with objects can contribute to managing technological innovation across specialized knowledge networks**.

Conceptualizations of the *objects* and *staging* concepts that define this enquiry are unfolded in the following subsection.

2.3. ELABORATIONS ON *STAGING* AND *OBJECTS*

In a forthcoming anthology, Pedersen et al. (2020, forthcoming) introduce ‘staging’ as a concept influenced by the work of Goffman (1959) and symbolic interactionism, STS scholarship and the Scandinavian tradition of participatory design. According to Pedersen et al., Goffman was concerned with identity creation as something performed through negotiations, whereas the STS and participatory design scholarship address how collaboration between actors in design of or with technology is seen as something to be performed based on negotiations across diverse perspectives and understandings of the world. Pedersen en et al. proceed to position staging as a repertoire of methods by which interactions across actors and objects can be configured and facilitated and suggest this repertoire as a possible alternative to the mainstream sequential and stage-gate models that dominate as means of planning and control. The mainstream models challenged by Clausen et al. are not only dominant within academic endeavors. Similar assumptions also proliferate in industrial settings, where they are supported by a variety of management tools thought to enable an assumedly mechanistic and rational process of development (Bates and Clausen 2020; Narayanamurti and Odumosu 2016; Szajnfarber and Weigel 2013; Vinck 2009b).

In my own chapters in the anthology (Bates 2020a, forthcoming; Bates and Juhl 2020, forthcoming), I reflect on ‘staging’ as “a practice by which *entities* (i.e. networks composed of humans and non-humans, material and immaterial objects) are materialized and (re)assembled to perform in processes of translation” (Bates 2020, fortcoming). These reflections take outset in ANT and the work of Clausen and Yoshinaka (2009: 2) who draw from science and technology studies to consider the roles of devices and how these devices intervene at the front end of innovation. My notion of s*taging with objects* is also influenced and inspired by the concept of ‘sociotechnical spaces’ (Clausen and Yoshinaka 2005, 2007), which combines a political process approach with ANT, and challenges the roles played by ‘product concepts’ and ‘problem identification tools’ in the design process by asking how such devices are translated into concrete organizational practices. Although Clausen and Yoshinaka’s staging concept is well-suited for considering how the contexts of engagement within sociotechnical ensembles can be addressed, politicized and acted upon, the concept is intended more as a ‘sensitizing concept’, than a well-delineated tool (ibid). Expanding upon the work of Clausen and Yoshinaka, Clausen and Gunn (2015) develop the concept of ‘temporary space’, narrowing the scope of the sociotechnical space concept to target a more specific endeavor.Whereas Clausen and

Yoshinaka (2005, 2007, 2009) developed 'sociotechnical space' to focus on FEI and the design process in more general terms, Clausen and Gunn (2015) present 'temporary space' to specifically consider 'user-oriented innovation' that falls "outside or on the fringes of institutionalised practices" (ibid: 87). By considering intermediary objects as networks that include both human and non-human elements, Clausen and Gunn address the staging of intermediary objects within temporary spaces and how these objects perform in practice. Clausen and Gunn then trace relations between the performance and configuration of these intermediaries in order to illuminate how "knowledge [is] generated, packaged, transported and unpacked" (2015: 77) through *staged* interactions between end-users and designers.

For the purposes of this dissertation, Bates and Clausen (2020) also consider *staging* within *temporary spaces,* albeit in the context of industrial technology development. Their findings include, that the problematizations by and for which objects are initially staged can perform to engender additional, unexpected and sometimes destabilizing actions and objects. This finding is wholly in-line with a key tenant of SST scholarship, that *translation is fragile* – strengthened and weakened by a diversity of (dis)connected elements and a clear extension of the work of Clausen and Yoshinaka. It also aligns with Callon's postulate that "[p]roblems are not spontaneously generated by the state of knowledge or by the dynamics of progress in research. Rather they result from the definition and interrelation of actors that were not previously linked to one another" (Callon 1984: 228). Extending this line of thinking to staging with objects, it becomes apparent that the sheer scope of actors and objects involved in industrial technology development makes the intentional *staging* of such *link*s (or as Latour calls them 'associations') eminently complicated. Here, the staging perspective sensitizes attention to strategic choices oscillating between two extremes – whether to risk the premature black-boxing of open networks (typically a management failure – see Gish and Clausen 2013), or to keep as many associations as possible open indefinitely? As Latour suggests, the first consequence of a successful mobilization and its 'instruments' is that it will be accompanied by "a flood of inscriptions and specimens" (Latour 1987: 233). It is thereby important to remember the 'ideal' recommended by Latour when (re)situating one's instruments: Retain as many elements as possible within a center of calculation while still being able to manage them (ibid: 237). This is a principle aspect of *staging with objects* and is addressed in the methodological framework of Chapter 5.

As this elaboration intends to make clear, s*taging* is by all accounts a 'material semiotic' endeavor. Taking form in "weaves that are simultaneously semiotic (because they are relational, and/or they carry meanings) and material (because they are about the physical stuff caught up and shaped in those relations)" (Law 2019: 1). SST scholarship includes a variety of concepts concerning the performance of objects and devices within (and across) different developmental contexts. Here it is important to note that while I differentiate between conceptualizations according to the definitions and intentions of their architects, I do not differentiate between 'objects' and ‘devices’ (or ‘instruments’ ‘models’ and ‘tools’). Drawing on Star (2010: 603), an object’s materiality is rooted in action, “not from a sense of prefabricated stuff or ‘thing’-ness”. In line with Vinck (210: 220), ‘objects’ can also be concepts: “Conceptual work involves a broad material exercise in writing, correction, deletion and rewriting, on paper, on the board and on computer. Some of the ‘abstract’ work can, therefore, be entered in its materiality”. Although the architects of the objects considered here may designate a concept as an *object* or a *device* and I respect these designations when referring to them, I use *object* as a common designation for both. For the purposes of this dissertation, *staging with objects* is equivalent to *staging with devices* (or *instruments, models* and *tools*).

Of the concepts presented here[11], the ‘boundary object’ concept, initially presented by Star (1989), and further developed by Star and Griesemer (1989) and Bowker and Star (1999) “has enjoyed a [particularly] vigorous academic career” (Trompette and Vinck 2009). As a concept, the ‘boundary object’ is rooted in an early ontological controversy within the ANT community. Star and Griesemer (1989: 390) took issue with the way devices of interessement and OPP “can be seen as a kind of ‘funneling’ – reframing or mediating the concerns of several actors into a narrower passage point” that favors a single point of view. Star and Griesemer thus propose an alternative, ‘many-to-many mapping’ to describe how different groups can support each other in independent work arrangements, where several OPP are negotiated across several kinds of allies (ibid: 389). The concept of ‘boundary objects’ thereby involves a many-to-many process of interessement.[12] From this vantage, collaborating entrepreneurs reduce local uncertainty while maintaining coordinated cooperation between allies through an “indeterminate number of coherent sets of translations” (ibid 390-391). As such, the concept of ‘boundary objects’ is designed to consider “the *flow* of objects and concepts through [a] network of participating allies and social worlds” and is focused on understanding processes of management occurring *across* these allies and worlds (ibid: 389). That the boundary object “allows different groups to work together without consensus” (Star 2010: 602) makes the concept eminently suitable for analyses of translations *intersecting* social worlds. Still, this definition implies a form of stability that limits its applicability in other analytical contexts. Boundary objects must remain “both plastic enough to adapt to local needs and the constraints of the

[11] This discussion of objects is a re-working and expansion of a review on, *the role of devices and objects in development processes* by Bates and Clausen (2020: 14-16).

[12] This notion of objects stems from a pragmatist view of social worlds from the ‘symbolic interactionism movement’. According to Vinck (2012: 93): “These ‘social worlds’ are groups of activity having neither a clear border nor a formal and stable organization. These are built up through the relation between social interactions generated by the primary activity and a suitable definition of reality”.

several parties employing them, yet robust enough to maintain a common identity across sites" (Star and Griesemer: 392-393).

In contrast, the concept of 'intermediary objects' presented by Vinck et al. (1996) is suitable for analyses independent of intersections or consensual requirements. Because of its intentionally weaker conceptualization, the 'intermediary object' is "open to interpretation in terms of the mechanisms at work", making it useful across a broader variety of situations (Vinck 2012: 94). This weaker conceptualization is achieved by separating intermediary objects into two different roles: 'commissioning objects', which passively serve "rational and appropriate means of pursuing specific objectives", and 'mediating objects' that include both "actions and mediations" with "active and interactive roles" (Vinck et al. 1996: 302). According to Vinck et al. (ibid), these categories are extensions of "Latour's voluntarily materialistic point of view […] that there is a proliferation of [hybrid] intermediary objects" commuting between different roles (ibid: 299). Unlike boundary objects, which rest at the *intersections* of social worlds, intermediary objects are 'on the move' – they *accompany* processes 'in the making' and are mutually shaped in interaction with these processes (Vinck 2012). Put simply, the *identities* of intermediary objects can change (Vinck 2011, 2012). To analyze these changes, Vinck (2011) presents the 'equipping of intermediary objects' and demonstrates how this equipping process "leads to a better understanding of the co-construction of people and of practices in design and engineering" (ibid: 26). Here, Vinck defines equipping work as "the collective activity that involves agreeing about the features to be added to intermediary objects so that they can be enrolled in the space of exchange between actors" (ibid: 25). Accordingly, concerns "about the equipping of intermediary objects [are] precisely related to th[e] issue of objects switching from one ontological status to another" where the equipping process itself enables intermediary objects "to be connected to conventional supports and spaces of circulation" (ibid: 38). This type of equipping work is explicitly considered in two of the dissertation's cases (Bates 2020b; Bates and Juhl 2020).

The concepts of boundary objects and intermediary objects have significant differences. Whereas first "aims to understand how several social worlds are cognitively synchronized", the latter is more suitable for considering "networks of relations between research groups" (Vinck 2012: 94). Still, the architects behind both concepts "strive to account for the materiality of things that actors produce and use in a given situation" (ibid: 93-94) and have been used together to analyze these different aspects of work arrangements. Vinck et al. (1996) drew on the concept of boundary objects to support their initial analysis of how intermediary objects oscillate between commissioning and mediating roles, and Vinck's later work even considers how intermediary objects are intentionally transformed into boundary objects through an equipping process (Vinck 2011; 2012). Similarly, I find both concepts useful in my analyses. From a helicopter perspective, the case on industrial-academic collaboration represents a meeting of different social worlds, where the case on translation from invention to commercialization is more akin to different research groups working together. But both concepts were meaningful when considering the different cases from a frog's-eye view – revealing *different* aspects of the micro-processes involved in *staging with objects*. In the case on translation from invention to commercialization, the boundary object concept was useful in describing TRL as "an invisible infrastructure structuring the relation between different social worlds" (Bates and Clausen 2020: 32), and in the case on industrial-academic collaboration (Bates and Juhl 2020, forthcoming: 208) document "the upstream constitution and configuration of an intermediary object to perform as a boundary object". This shows that analytical choices between using these conceptualizations are highly dependent on the reading of the situation under study.

Staging with objects also involves '(re)writing devices' (Callon 2002) and 'calculative devices' (Callon and Muniesa 2005). *(Re)writing devices* are another example of what Latour (1987: 233-237) terms 'centres of calculation': The literal or metaphorical 'sites' which allow spokespersons of all sorts, from sea captains to laboratory managers, to hold a variety of elements in circulation while still being able to manage them. Callon (2002: 193) defines 'writing and rewriting devices' as follows:

> They are important in establishing and transforming systems of collective action because they work by a method of *successive adjustment*. They also make possible the progressive expression of demands that are partially undetermined, and the definition of actions needed to respond to such demands. Finally, they make the complexity of systems of action manageable and controllable without eliminating it.

Although the 'service sector' from which Callon developed this concept can initially seem very different from the development contexts of the off-highway mobile industry, the *varied and evolving organizational tools for managing complexity* used in both sectors have more in common than first meets the eye. According to Callon, coordination becomes most difficult in situations where customers are not paying "for a specific material good but [rather] for the organization of a complex system of action that enables them both to progressively become aware of what they want and to express and fulfill this wish" (ibid: 192). Within this complex system of action, (re)writing devices possess an important *centralized* function. By providing actors with the ability to calculate, (re)writing devices render decisions calculable *for a single point* and *from a specific location.* This allows (re)writing devices to simultaneously define, describe and prescribe action – even as they serve to reconfigure collective and individual action. (Re)writing devices support organization in locations between 'knowing and acting'. This makes (re)writing devices particularly useful for analyzing investigations that are focused on *how* a technology is redefined within development processes where the expected criteria for the technology's performance are articulated and revised in real-time (see Bates and Clausen 2020).

Callon and Muniesa (2005) posit 'calculative devices' as a framework for describing processes of 'economic network-stabilization'. Once again, the emphasis is on "material movement and *centers of calculation*, but as something new, Callon and Muniesa are concerned with what calculation *does*, in ways that blur *a priori* distinctions between judgement and calculation. "Calculation starts by establishing distinctions between things or states of the world, and by imagining and estimating courses of action associated with those things or with those states as well as their consequences" (ibid: 1231). According to Callon and Muniesa, such calculations are made possible through *calculative devices.* A key characteristic of these devices is that they possess three calculative moments – the *circumscription* of agencies, the *organization* of encounters and the *establishment* of conventions. – where these moments make it possible for "goods [to] be calculated by calculative agencies whose encounters are organized and stabilized" (ibid: 1245). Although Callon and Muniesa do utilize economics to speak with economists, they are also addressing processes of economic network-stabilization to consider how a calculative device performs configurative tasks in 'a cycle of accumulation'. It is the latter part of this endeavor that makes the calculative device concept equally useful for addressing processes of *technological network-stabilization* (see Bates and Clausen 2020). Revisiting Latour (1987: 222):

> All the distinctions one could wish to make between domains […] are less important than the unique movement that makes all of these domains conspire towards the same goal: a cycle of accumulation that allows a point to become a centre by acting at a distance on many other points.

This is the crux of the *staging with objects* conceptualization and the methodological framework for managing technology development towards which this dissertation strives. The following chapters present how conceptualizations of objects performing as *boundary objects*, *calculative devices*, *devices of interessement*, *intermediary objects* and *(re)writing devices* can provide viable means for identifying, analyzing and ideally developing *cycles of accumulation* through which technologies transition from invention to commercialization.

2.4. SUMMARY OF CHAPTER 2

This chapter intends to emphasize the conditional and unpredictable nature of sociotechnical processes and outcomes, the complicated associations that connect actors, conceptions of technology and its function, and how these conceptions are necessarily adapted across unexpected contexts.

Subsection 2.1 introduces recent scholarship addressing the sociotechnical in engineering practice, considering how the research intentions of this dissertation align with established SST theory and practice. The subsection concludes by delimiting the concepts considered for theoretical reflection to include only those which: a) could be introduced, by me, into 'on-the fly' discussions with engineering and management colleagues to support impromptu reflections on the nature of the micro-processes in which we found ourselves, and; b) resonated with colleagues insofar as these concepts seemed to expand, rather than impede, our dialogues.

Subsection 2.2 introduces sensitizing concepts and key tenets from the 'broad Church' of STS scholarship. Concepts presented include *translation*, *moments of translation*, *heterogeneity (heterogeneous engineering)*, *semiotic relationality, centers of calculation* and *matters of concern*.

Subsection 2.3 elaborates on *staging* and *objects,* cross-referencing the foundations of the staging concept presented here (*sociotechnical spaces*, *temporary spaces*) with the intentions of this dissertation. Concepts of objects and devices were also unfolded, including, *boundary objects*, *intermediary objects, (re)writing devices* and *calculative devices.*

The remaining chapters of this dissertation are rooted in the foregoing deliberations and are structured as follows.

- Chapter 3 expounds the methodological considerations upon which this dissertation rests.
- Chapter 4 presents a discussion wherein empirical material from the two cases is analyzed from the perspectives of STS theory presented in Chapter 2, that is in turn structured according to its relevance for the research question and three sub-questions.
- Chapter 5 draws from the preceding chapters to develop and present a methodological framework for managing technology development in industry.
- Chapter 6 includes reflections over the academic novelty and shortcomings of this dissertation in light of the intentions declared in Chapter 1. It also considers the limitations and implications of the developed methodical framework for engineering practice.
- Chapter 7 is the Appendix of the papers which frame this dissertation.

3. METHODOLOGY

The ability to move technologies from invention to commercialization is widely accepted as a key parameter for the success of industrial firms, both within SST scholarship (Clausen and Yoshinaka 2005, 2007, 2009; Clausen et al. 2012; Gish and Clausen 2013; Legardeur et al. 2004, 2010) and in more prescriptive innovation management literature (see Cho and Eppinger 2005; Cooper 2006, 2008; Garg et al. 2017; Herstatt et al. 2004; Markham et al. 2010). What sets this dissertation apart from previous studies, is that it strives to both *investigate* and *improve* the micro-processes of managing technology development from my perspective of a *practitioner-analyst* while remaining a practitioner and putting own individual practice into the vocabulary of the analyst. In a recent review, Mody (2020:2) framed the closest analogues to my specific endeavor as a probably being "classic sociological and ethnomethodological studies of musicmaking by practicing musician-sociologists", naming the work of Sudnow as particularly relevant.

In *Ways of the Hand*, Sudnow (1978) leverages extensive childhood classical music lessons as an adult to accomplish and acquire improvisational jazz skills on the piano. This required immersion into the theory and practice of a new field, where previous tactile knowledge of the instrument was both re-contextualized and re-conceptualized to accommodate necessities of the new endeavor. In many ways, this experience harmonizes well with my own and opens for some relevant methodological considerations. For example, we both draw on skilled practice to achieve new competencies at the intersections of *different social worlds*. In my case, I am referring to the different worlds of practice and theory, *and* the different worlds of industry and academia. To accommodate large overlaps between the worlds of 'practice and industry', and between the worlds of 'theory and academia, I utilize the 'practitioner-analyst' metaphor (Mody 2020) to describe these different (composite) worlds. The term *practitioner-analyst* also aptly describes Sudnow's work. Still, there are notes of discord between our endeavors. Sudnow could apply practice from one world without having to re-apply it in the other. While both Sudnow and I leverage tactile skill in new contexts, Sudnow could pursue immersion in jazz independently of the classical music scene (in which he had never worked professionally), whereas I needed to both position and *maintain* high efficacy in all aspects of my current skills while simultaneously leveraging them towards the acquisition of new ones – that I might continue my employment in both. Sudnow could, and did, abandon tactile arrangements (from his classical music instruction) which were unnecessary or inhibiting for the acquisition of different types of tactile mastery; for me this was impossible. Although neither Sudnow nor I were confined to the intersection of different social worlds, both my *material sustenance* and *continued access* to academia were deeply rooted in my performance in industry. It quickly became apparent that whatever methodology I pursued must assist me in recognizing, accommodating and leveraging this duality.

With these considerations in mind, this chapter is structured as follows.

- Subsection 3.1 considers the implications of my different incentives – to span the worlds of both *practitioner* and *analyst* – by drawing on auto-ethnographic theory to deliberate how the *duality* of researching my own industrial practice can be accommodated.
- Subsection 3.2 introduces the concept of ‘following the objects’, as a means of understanding networks where actors devote “a considerable amount of time to designing, negotiating, producing and disseminating all kinds of *objects*”, and where the resources associated with these activities imply their importance for interactions inside of the networks (Vick 2011: 26-27).
- Subsection 3.3 shifts attention to the research design *writ large,* presenting the ‘Biography of Artifacts and Practices’ (BOAP) framework (Hyysalo et al. 2019) as a means of structuring and analyzing my empirical material. According to Hyysalo et al., establishing an adequate picture of how technology takes shape, requires that both the wide range of sites where the technology evolves and the connections between these settings be investigated.
- Subsection 3.4 summarizes and reflects on the methodological considerations of Chapter 3, to make sense of my industrial practice in preparation for the discussions of Chapter 4.

3.1. ACCOMMODATING THE DUALITY OF AUTO-ETHNOGRAPHIC STUDY

From my first managerial position in 2013, I have sought satisfactory academic frameworks for assisting technology managers and engineers in operationalizing the complex process of moving a technology from idea to implementation. My Industrial PhD research was thereby instigated at my behest, and stems from an innate desire to improve the abilities of the Work Functions (WF) division to manage technology development within and for the off-highway mobile hydraulic market where it operates. My own tasks within this operation include: responsibility for defining and executing the technology roadmap for the business unit (BU) where I am employed; managing technology development projects and initiatives across R&D, production and testing facilities in China, Denmark, Poland and USA; improving BU competencies in advanced measurement, testing and simulation techniques through cooperation with other Danfoss segments and divisions, and collaborations with leading universities in Europe and China; supporting functions and colleagues by facilitating specialized knowledge and know-how, and; developing patents. As my motivation suggests, I identify as a *complete member researcher* (CMR, Adler and Adler, 1987; Anderson, 2006). A researcher, “possess[ing] the qualities of often permanent self-identification with a group and full internal member-ship, as recognized both by themselves and the people of whom they are a part” (Hayano, 1979: 100). Hayano (1979) calls this type of ethnographic research *auto-*

ethnography.[13] or "the cultural study of one's *own people*" (Adler and Adler, 1987: 4) – including "the researcher's involvement and intimacy with his subjects (Hayano, 1979: 99)". Auto-ethnography is not the focus of my research, but rather the channel by which my research is conveyed. In the following, I consider auto-ethnography as conduit for considering how the dual roles of technology manager and budding researcher can be channeled and accommodated.

According to Adler and Adler (1987), a complete member researcher (CMR) role promises clear advantages. First among these, is that that CMR are "less frequently exhorted [by other members of the group] to present the group favorably, or to keep the group's secrets" (ibid: 12). Adler and Adler submit that this could be related to the *nature of the exchange*; CMR receive considerable latitude for having yielded themselves to the group in previous contexts. Having never pursued other types of social science research, I cannot attest to the levels of secrecy, exhortation or latitude granted to me by my *informants*. Still, the statement, while flattering, idealizes my own experiences. For the *researcher in the wild*, the fate and the survival of the group are *always* at stake – our identities and elaboration of knowledge are intertwined (Callon and Rabeharisoa 2002). This *stake* not only makes *exhortation* superfluous; it permeates all aspects of the research. Our identities are "common and shared before being individual" (ibid: 203).

For the auto-ethnographer, associations are also confounded in *action*. As Anderson notes (2006: 380): "Unlike their peers in other research setting(s), auto[-]ethnographers must orient (at least for significant periods of time) to documenting and analyzing action as well as to purposively engaging in it". Balancing an identity between these often-conflicting dimensions has been termed "a near-schizophrenic multiple focus" (Adler and Adler 1987: 5).[14] To accommodate this duality, I employ the *five key features* of 'analytical autoethnography' to reflect on my own research practice. Anderson (2006: 378) defines these *key features* as involving: "(1) complete member researcher (CMR) status, (2) analytic reflexivity, (3) narrative visibility of

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[13] Drawing on Hayano (1979), I utilize the hyphened *auto-ethnography* to denote this specific ethnographic practice. *Sans* hyphen, *autoethnography* is oriented towards the researcher's personal identity and desire to understand and maintain coherence in the course of life, in a writing and relay genre that it is interpreted personally in a cultural context (Baarts 2015). As not all researchers adequately "signal the use of self-observation, a study of his or her own group, or both" (Czarniawska 2014: 56) when using the term, I place a hyphen in citations concerned with complete member researchers.

[14] This is also true semantically: Czarniawska (2014: 56) "avoid[s] the term 'autoethnography' because, as literally understood, it would assume a multiple personality disorder (ethnos means 'people')".

the researcher's self, (4) dialogue with informants beyond the self, and (5) commitment to theoretical analysis".

The motivation to pursue an SST focused Industrial PhD *with outset in my own practice as a technology manager and engineer* takes outset in my CMR status. Anderson (2006: 382) defines the second feature, 'analytical reflexivity', as involving:

> [A]n awareness of reciprocal influence between ethnographers and their settings and informants. It entails self-conscious introspection guided by a desire to better understand both self and others through examining one's actions and perceptions in reference to and dialogue with those of others.

Although Anderson's 'analytical reflexivity' is specifically related to CMR status, I purport that it has equal relevance for, and can be addressed through, the *staging with objects* practice towards which this dissertation strives. As a *technology manager* in the WF division, I must accommodate 'reciprocal influences' between my decisions and actions within the development space on its actors, objects and activities, while also serving as the space's primary informant. As I argue in Chapters 4 and 5, successfully predicting, perceiving and accommodating these reciprocal influences in my engineering and management practice requires reflective endeavors by which these influences, usually in dialogue with my colleagues, can be considered. I submit these endeavors can also serve to accommodate the duality of my CMR role. Bates and Juhl (2020, forthcoming) contextualize this type of research as being performed by actors integral to the work by which an organization subsists, and encompassing "a skilled management practice different to that performed by researchers and consultants who are not embedded within the locally situated understanding of the objects they observe (and may or may not reciprocally manipulate)". Within this practice, numerous objects perform to "underwrite the processes and goals they are situated to support" (Vinck 2011). Considering the *reciprocal manipulation* of these objects as a *specific dialogic process* between and across human and non-human actors (Bates 2020a; Bates 2020b; Clausen and Bates 2020; Bates and Juhl 2020; Jul and Bates 2020), I posit that dialogues inherent to industrial development of technologies, both provide and insist that "examination of one's reciprocal actions and perceptions in reference to and dialogue with those of others" takes place – in a context equally relevant, albeit more general, to that suggested by Anderson (2006: 382-383). The challenge thus becomes to expand case relevant dialogues, that are typically focused on *engineering* sciences, to include relevant conceptualizations from the *social* sciences with the intention of making the mutually shaping intersections between my 'Complete Member' and 'Researcher' roles more transparent. Consider an example of this *dialogic* process from Bates and Clausen (2020: 11-12). In a team meeting that immediately followed a larger technology readiness assessment meeting about a novel steering technology, controversies arose around the usefulness of the TRL tool that the team was expected to use. Drawing on STS theory to (re)conceptualize *technology readiness levels* and their role in the technology development process, I shared what it was like for me to use this tool in my roles as 'assessment facilitator' in the previous meeting. This opened for group reflections with my team around how my own theoretical lens, as a social science researcher, was simultaneously influencing our engineering practice.

Anderson (2006: 384) terms his third key feature 'narrative visibility of the researcher's self', which he defines as follows:

> Auto[-]ethnographers should expect to be involved in the construction of meaning and values in the social worlds they investigate [… and] should not necessarily shy away from participating in potentially divisive issues.

As an acting manager, I play a significant role in the *divisive issues* that propagate the cases of this dissertation. Serving as a principle spokesperson for the technologies and their processes of development, my involvement in the *construction of meaning and values* occurring within these development spaces is an essential part of my employment. Some examples of controversies from which I have not *shied away*, include: (Re)defining the nature and intentions of how established 'management tools' (i.e. the *TRL figure of merit* and company-tailored *stage-gate models*) were employed within the WF Division (Bates and Clausen 2020); (Re)situating conceptualizations of functionality to accommodate the unexpected demands fostered through business-to-business interactions in a transition from invention to commercialization and respond to the dynamic demands of *top management* (Bates 2020a, forthcoming); The (re)definition of principle goals and success criteria in order to maintain 'referential alignment' in an industrial-academic collaboration spanning different organizational and institutional settings across differing performance expectations (Bates and Juhl 2020, forthcoming; Juhl and Bates 2020) and finally; (Re)positioning a series of patents to perform as a cohesive coordinating device in a process of technology development, when established management tools fell short of their initial intentions (Bates 2020b).

Such in-depth involvement is also relevant to Anderson's fourth key feature, 'dialogue with informants beyond the self'. While Anderson does not explicitly define *dialogue*, he states that, "[t]he ethnographic imperative calls for dialogue with *data* or *others* [… and reflexivity] more appropriately understood as a relational activity" (ibid: 386). The tasks associated with my 'day job' (listed at the start of this subsection) all require constant interaction with data *and* others, albeit in the practical sense described earlier in this subsection under *reciprocal influence*. Theoretically, I find Anderson's *ethnographic imperative* congruent with an understanding of "dialogue" as a term used in "non-normative and non-restrictive ways to refer to all the activities of co-construction that take place in interaction, whether these activities are considered positive or negative" (Cooren 2010: 1). Building on Cooren and Sandler's (2014: 227) proposition that "stand[ing] in a dialogic relation to a person, action, [object] or utterance means to respond to it", I consider my own role in the dissertation's cases as instigating a series of *dialogic relations,* mutually shaped by the objects, actors and activities which may or not have been set into motion by me or my colleagues, but to which we must nonetheless respond. Such dialogic relations are addressed explicitly in two of the publications included in this dissertation. Viewing the TRL as a 'calculative device' (cf. Callon and Muniesa 2020), Bates and Clausen (2020) consider how the TRL device was employed as "[a] provoking dialogic instrument – shaping and reshaped in a process of development […] that produced agreement on the objects and conceptualizations it helped to mobilize and the problematizations these engendered" (ibid: 29). Addressing the complexities of industrial-academic collaborations, Bates and Juhl (2020, forthcoming: 208) reflect over how a "test-setup became more than a means for demonstrating the functionality and reliability of the new environmentally friendly lubricant – it also became a dialogic tool for negotiating established concepts of validity". To further accommodate 'narrative visibility' within these publications, I make attempts to "illustrate analytic insights through recounting [my] own experiences and thoughts as well as those of others" and to present myself as "grappling with issues relevant to membership and participation in fluid rather than static social worlds" (Anderson 2006: 384).

The fifth and final key feature of analytical autoethnography is a 'commitment to theoretical analysis', where Anderson (2006: 387) postulates, "the defining characteristic of analytic social science is to use empirical data to gain insight into some broader set of social phenomena than those provided by the data themselves". My theoretical focus stems from SST concepts that are shown adept in divulging complex relationships between how facts (e.g. notions of a technology's *functionality* and *reliability*) are developed through staged negotiations (Latour 1987; Latour and Woolgar 1979). Nevertheless, most of these concepts were developed for different applications than to those which I deploy them. To ensure juxtaposability of these concepts into the contexts of the dissertation, in dialogue with colleagues, the 'theoretical background' presented in Chapter 2. only includes concepts for theoretical reflection which: a) could be introduced, by me, into 'on-the fly' discussions with engineering and management *colleagues* to support impromptu reflections on the nature of the micro-processes in which we found ourselves, and; b) resonated with my colleagues insofar as these concepts seemed to expand, rather than impede, our dialogues. This is also meant to support development of the methodological framework of Chapter 5, which intends to stimulate reflective practice in technology managers and engineers employed in industry.

My *commitment to theoretical analysis* and the collection and selection of empirical data is further expounded in the following subsections on 'following objects' (Subsection 3.2), and the 'BOAP framework' (Subsection 3.3).

3.2. FOLLOWING OBJECTS IN CASES OF TECHNOLOGY DEVELOPMENT

According to Vinck (2010: 203), scientists establish *facts* through interaction with a variety of artefacts. Here, "[t]he 'fact' rarely imposes itself. Researchers learn how to produce it and how to distinguish it from the artefact thanks to various manipulations and critical examination" (ibid). While this dissertation differs in focus from the early laboratory studies to which this citation refers, Vinck extends this thinking to scientists and laypersons, manipulating artefacts in other contexts – be they *boundary objects* at the intersections of social worlds (Vinck and Trompette 2009, 2010) or *intermediary objects* cycling between *commissioning* and *mediating* roles (Vinck 2009a, 2010, 2011, 2012; Vinck et al. 1996).

Because an object "constitutes a trace and a mark of its authors and their relations", Vinck (2012: 95) suggests that following such objects "tells us something about its authors and the sociotechnical conditions of their activity, about the paths they follow and the contingencies that arise". In the edited volume, *Everyday Engineering: An Ethnography of Design and Innovation* (Vinck 2009a), diverse authors formally trained in both engineering and sociology "propose an ethnographic approach to technologies that takes objects into account just as much as human beings" (ibid: 2). This approach builds on the early work of Vinck et al. (1996: 318) in following "objects at the core of the design process" in an industrial case:

> Intermediary objects are deeply hybrid, mixing materiality, authority, covenant and trust. They always present a complex, intentional and ideal reality in connection with their origin, both factual and material due to their inter-objective and inter-subjective destination. It is at their level that constant shifts, implementation and transformations take place.

My collection and selection of empirical material places a similar emphasis on objects. Through involvement in specific industrial cases (Chapter 1.5, above) I follow objects performing as *boundary objects*, *calculative devices*, *devices of interessement*, *intermediary objects* and *(re)writing devices* (Chapter 2, above) to identify relations in heterogeneous networks comprising specifications, test-rigs, technicians, engineers, methods of analysis, and conceptualizations of functionality and reliability – to name a few elements. Aspects of the collection process are described in (Bates 2020a, forthcoming). In addition to a journal, my empirical data stems from specifications, sketches, analyses, emails, reports and audio-recordings made or collected by or for me in my role of WF Technology Manager. These serve as tools for (re)considering actions, "in the order in which they happen and in the sensible order, given that the two things are practically indissociable for human beings" (Vinck 2009b: 3). By *sensible order* is meant the order that "makes sense to people […] linked to what they do, to the actions they carry out, and to the results and performances they obtain.

The papers of this dissertation show that the same objects can have different roles and/or serve different purposes. For example, Bates (2020a, forthcoming) shows that the *intermediary object* concept and how objects cycle between *commissioning* and *intermediary* roles adequately describes translation from invention to commercialization in a particular industrial setting. This is not true for Bates and Juhl (2020, forthcoming), who document the transformation of *intermediary objects,* through an 'equipping process' into *boundary objects* that can act as a center stage for technological development in an industrial-academic collaboration. Bates (2020b) investigates a similar process whereby mundane objects are positioned to perform coordinative work on par with more mechanistic management tools in order to equip *intermediary objects* with the properties of *boundary objects*. In a more complex process of development, Bates and Clausen (2020) find that *technology readiness levels* perform intermittently as *boundary objects*, *calculative devices*, *devices of interessement*, *intermediary objects* and *(re)writing devices* in the hands of skilled practitioners according to their needs. To demonstrate this process more fully, two brief examples of actions, sites, contexts, and controversies associated with some *followed* objects follow here.

Bates (2020a, forthcoming) identifies four objects associated with an assumedly mature technology and their composite elements: 1) a management tool (the *technology readiness level* figure of merit); 2) a *whitepaper* on 'pilot customer considerations'; 3) a *conceptualization* of hydraulic performance, and; 4) a *business case*. By following deliberate manipulations of these objects by specific collective actors, including the division's top management, Sales and, Technology Development Project teams, and key customers, across multiple meetings, laboratories and, company and customer test-tracks in Denmark and abroad, the paper documents *how* these manipulations (un)intentionally (dis)aligned the composite elements comprising the objects and ultimately perform to de- and re-stabilize the larger sales and R&D networks into which the objects were initially and finally (re)assembled.

The book chapter by Bates and Juhl (2020, forthcoming) and working paper by Juhl and Bates (2020) both investigate an industrial-academic collaboration, spanning laboratories and offices in Denmark and Sweden, to validate the functionality and reliability of an eco-friendly alternative to the petroleum-based hydraulic lubricant dominating the off-highway mobile industry. Focusing on the test-setup designed to validate the lubricant, Bates and Juhl find that the association of objects (e.g. company, industrial and academic standards, test and measurement equipment, and analytical tools) comprising the larger test-setup, performed to undermine the *referential alignment* necessary to sustain the collaboration. Moreover, decisions to continue the collaboration required the introduction of *additional* experimental tests and a new object, a ball-on-disc test-rig, which helped to alter the initial reasons for the WF division participating, and remaining, in the collaboration.

Following objects is a distinct SST perspective, viewing and "treat[ing] everything in the social and natural worlds as a continuously generated effect of the webs of relations within which they are located" (Law 2009: 141). My collection and selection of empirical data draws from *Everyday Engineering: An Ethnography of Design and Innovation* (Vinck 2009a) to consider "how technical action is entirely composed of meaning and performance" (ibid: 3). By utilizing Vinck's 'key methodological idea' (2012), of following material objects across sites and between actors, I am able to illuminate how these objects perform according to the intentions inscribed into them. Although this provides an adequate framework for collecting, selecting and analyzing empirical data at *case levels*, as evinced in the above examples, I must also handle empirical data at the scale of my PhD research – to generalize situated findings generated over *long periods of time*, across *multiple* and *particular* settings. In their 'Biography of Artifacts and Practices' (BOAP) framework, Hyysalo et al. (2019) address the same challenges (albeit on a larger scale than that of this dissertation, which is lesser concerned with *common* research designs in the SST field).

> A key insight from social shaping of technology research, for instance, has been that new technologies are formed in multiple, particular (albeit interlinked) settings, by many different groups of actors over long periods of time. Nonetheless, common research designs have not kept pace with these conceptual advances, continuing instead to resort to either intensive localised ethnographic engagements or broad stroke historical studies, unable to address both the intricacy and extent of the process in tandem (ibid: 1).

In the following section, I reflect over the utilization of the BOAP framework in my own research design. These reflections are guided by the fifth key feature of analytical autoethnography: A 'commitment to theoretical analysis', from which I might "gain insight into some broader set of social phenomena than those provided by the data themselves" (Anderson 2006: 387).

3.3. DRAWING ON THE BIOGRAPHY OF ARTIFACTS AND PRACTICES FRAMEWORK FOR MULTI-SITED ETHNOGRAPHIES

The 'Biography of Artifacts and Practices' framework (BOAP, Hyysalo et al. 2019; Williams and Pollock 2012, 2009) builds on the idea, proposed by Kopytoff (1986), "that artifacts would have 'biographies' that feature different states of existence in connection to the social relations wherein they become to feature" (Hyysalo et al. 2019). In the following, I posit that a focus on *artefacts* and their *biographies* is also in line with the intentions of this dissertation to 'follow objects' towards understanding and improving industrial practice – despite this study falling outside of Hyysalo et al.'s *precise* characteristics of the BOAP framework.

Arguing for 'multi-site, longitudinal studies' that move beyond unrelated studies of the 'intricate practices' of particular settings, Hyysalo, Pollock and Williams (2019; Williams and Pollock 2012, 2009) propose that an adequate picture of how technology takes shape, requires that *both* the wide range of sites where the technology evolves *and* the connections between these settings be investigated. They call this "a move from *snap shot* studies [now prevalent in the STS community] to the linking together of *a string of investigations*" (Hyysalo et al. 2019: 4), and describe it as well-suited the call of Marcus (1995) for 'multi-sited ethnography' (Hyysalo et al. 2019: 6).

Although this dissertation is not exactly 'single-sited', it probably does not fulfill the stringent criteria for *multi-sitedness* voiced by BOAP's architects. Nevertheless, the dissertation's three-year study is indeed a product of associations which I have been a part, or leading, since at least 2005 (Bates and Juhl 2020) and in which I continue to have a stake. Although the "ecologies of interconnected actors" considered here lack the breadth of BOAP studies described by Hyysalo et al. (2020), I submit that the complexity of associations within the ecologies under study, *'goes beyond' current analytical templates and research practices* (ibid: 4) and thereby necessitates a *different* methodological approach than these current practices. An approach to which BOAP is well-suited. This dissertation certainly does not meet all of BOAP's extensive criteria, but it remains an initial step *towards* a multi-sited longitudinal objective of studying technology development with outset in my own practice. Whereas the focus of BOAP's architects is more closely tied to *Artifacts,* such as 'Enterprize Systems' and the varied practices of diverse individuals tied to the introduction and utilization of these systems, my emphasis is rather on the *Practices* in BOAP – or more precisely, *my own practice* of managing technology development over the last 15 years across different sites through the *staging* of different objects. Hyysalo et al. (2019: 6) define BOAP as a methodological approach to the study of sociotechnical change, and provide "eight recurring characteristics, which can be considered core markers of the approach". In the following, I briefly present the eight characteristics and reflect over their relevance – if not equivalence – to my own research agenda.

According to the first characteristic, "BOAP studies must have sufficient spatial and temporal reach to empirically engage the dynamics of the studied phenomenon" (Hyysalo et al. (2019: 5). As stated in Chapter 1.4, the selected cases represent two poles of technology development: a) attempts to move novel (albeit immature) technologies towards commercialization and; b) attempts to move established markets in directions where such technologies can be exploited by their inventors and collaborators. I posit the cases of this dissertation as representing a complex arrangement of mutually shaping multi-sited phenomena through which technology development practice can be investigated. But again, my definition of *multi-sitedness* likely diverges from that of Hyysalo et al. (2019) The dissertation's sites of study are all fostered by my role in (if not always located at) the host company and many of these sites are often reoccurring. Moreover, the 'objects followed' are often situated within the same measurement and test facilities or, albeit more rarely, the same equipment – be it located at facilities within the host company, its customers or collaborators. Nevertheless, I submit that the *focus* of my research, its *spatial and temporal reach* – while not wholly in line with a study of a *specific* technology (e.g. 'Enterprize Systems' or 'Greek Banking', cf. Hyysalo et al. 2019) – remains sufficient *towards a study of practice* with and across a *diversity of artefacts* involved in industrial technology development. As such, my spatial and temporal reach are perhaps more closely aligned with Marcus' proposition than with the BOAP framework (ibid: 3):

> Multi-sited research is designed around chains, paths, threads, conjunctions, or juxtapositions of locations in which the ethnographer establishes some form of literal, physical presence, with an explicit, posited logic of association or connection among sites that in fact defines the argument of the ethnography.

My logic for pursuing *multi-sited longitudinal* research rests on assumptions that central objects play significant and different roles across multiple sites and the actors they encounter. In extension thereof, I posit that *following* such objects and how they are *reciprocally* manipulated in their passage through these diverse contexts can provide insights for improving technology development practice. It is uncertain if BOAP's architects would recognize this dissertation as correspondingly *longitudinal*; bearing in mind that the seminal 'Enterprize Systems' study through which BOAP was developed spans 24 years and is still going strong. Instead, this dissertation's 'breadth' encompasses a study of *technology development* in the off-highway mobile hydraulic industry, across three of the industry's key technologies: orbital motors (Bates and Juhl 2020; Juhl and Bates 2020), hydrostatic steering units (Bates 2020a; Bates 2020b; Bates and Clausen 2020) and hydraulic lubricants (Bates and Juhl 2020; Juhl and Bates 2020), where my earlier *tribological* research in hydraulic component interactions (Bates et al. 2020; Furustig et al. 2015a, 2015b, 2016) has enabled or engendered the cases. Moreover, the development of these technologies is studied across the measurement, patent, production, R&D, sales and test facilities of a market leader within the design and fabrication of the technologies (Danfoss AS 2020: 26 - 28-29; Osenga 2020) – in *interaction* with the company's customers and collaborators, and their counterpart facilities.

The second characteristic of BOAP states:

> The shaping of technology and practices must be viewed as taking place within *ecologies of interconnected actors*, and not only study the actors only with respect to how [they] affect the studied technology […] as this leaves aside the rationales by which they operate (Hyysalo et al. 2019: 7).

Distinct 'ecologies of interconnected actors' are certainly apparent in the dissertation's cases and I do attempt to make actors' rationales visible by documenting their actions through and with objects. In delimiting objects, I draw on 'Rules of Method' set by Latour (1987) and only includes objects from a network 'in action', considering only the *observed* performance of an object within the specific context that is under study (Bates 2020a, 2020b). Consider the following examples.

The dissertation's first case is associated with managing the translation from concept to commercialization in the off-highway mobile hydraulic industry (see subsection

1.4.2; Bates 2020a, forthcoming; Bates 2020b; Bates and Clausen 2020). In addition to the company's own management and patent offices, and measurement, production, R&D, sales and test facilities, the case includes three of the largest Original Equipment Manufacturers (OEMs) in the off-highway mobile industry, their R&D and sales teams, and test-tracks. Within this case, Bates (2020a, forthcoming) "responds to a limited understanding of the roles of objects within engineering management practice and how they are staged by managers and engineers" (ibid: 178), documenting controversies pertaining to an assumedly stable technology and unforeseen OEM demands to the functionality and reliability of the technology in vehicle architectures. Bates (2020b) "provides new insights into the detailed practices by which technology managers and engineers position objects to coordinate actors and action" (ibid: 213). The paper proposes that process models and figures of merit permeating industry are not unique in their ability to perform coordinative action and demonstrates how a series of patents were positioned to similar ends. Actors included the company's management and patent offices, test facilities, and R&D and sales teams responding to OEM demands for a unique system architecture. Bates and Clausen (2020) ask how the *technology readiness level* (TRL) figure of merit was made to perform as an effective coordinating device. Following the device across project meetings, Bates and Clausen consider TRL per the calculative device concept of Callon and Muniesa (2005), "to illuminate how TRL serves to circumscribe, configure and coordinate encounters and activity in a technology development project" spanning company assessment groups, test facilities, and R&D and sales teams (Bates and Clausen 2020: 137).

The second case is associated with an industrial-academic collaboration to commercialize a sustainable substitute for petroleum-based lubricants (Chapter 1.4.3; Bates and Juhl 2020, forthcoming; Juhl and Bates 2020). The ecology of this case is especially interesting. Within the collaboration, the WF division initially performed as a *de facto supplier* in the collaboration, as opposed to the more widespread role of *customer* that usually defines 'innovation science' – where "academic scientists produce knowledge for commercial ends" (Juhl 2016: 136). Here, WF defined the validation process for a lubricant invented at Luleå University of Technology (LTU, a leader in hydraulic and tribological simulations) and fabricated by an LTU spinoff company, while performing as an industrial laboratory through which the lubricant could be optimized for off-highway mobile applications. In this case Bates and Juhl (2020, forthcoming) investigate the intricacies involved in the *staging* by which referential alignment is created and sustained across the cooperating organizations and the industrial standards supporting dominant petroleum-based lubricants. Juhl and Bates (2020) consider *means* by which key elements of the collaboration (e.g. orbital gear-sets, ball-on-disc-experiments and the industrial test-rig) are made relevant to one another across diverse industrial and academic tools and standards. By analyzing the planning and execution of the consolidation of the academic and industrial knowledge practices, Juhl and Bates (2020) reveal the mechanisms connecting situated knowledges across different collaborative environments. Although the ecologies of my work are less extensive than the examples which Hyysalo et al. (2020) characterize as BOAP scholarship, the dissertation's cases and papers do provide a "varied interplay of multiple actors and actor-worlds, in effect introducing several scales and focal points of inquiry" (Hyysalo 2010: 40).

The third BOAP characteristic is: "Identify and research *interstices*, the moments and sites in which the various focal actors in the ecology interlink and affect each other and the evolving technology" (Hyysalo et al. 2019: 7). As the papers of this dissertation demonstrate, observing (or as in my role of technology manager, *positioning and receiving*) objects in contexts of technology development, serves to identify *interstices, moments and sites* – precisely because such objects define, expand and impede action *across* a diversity of stakeholders while mutually shaping the contexts into which they are situated. *Identifying and researching interstices moments and sites* is not limited to interactions with tangible substance. Bates and Clausen (2020: 11) "aim to illuminate the work of technology managers and engineers, and how they use concepts as devices to coordinate complex development projects in industrial settings".

The fourth BOAP characteristic is to "[p]ursue research at multiple temporal and spatial scales […] There is a need to bridge between the analyst's bird's eye view and the actors' real-time 'frogs' eye' perceptions" (Hyysalo et al. 2019: 7).The spatial and temporal scale of the industrial academic collaboration, provides an example of this *bridging*. Whereas Bates and Juhl (2020, forthcoming) mostly confine themselves to how micro-processes inherent to creating and sustaining an industrial-academic collaboration were *staged* across three participating organizations, Juhl and Bates (2020) take outset in Bates and Juhl (2020, forthcoming), to drill further into how the *technical minutia* of hydraulic components, tribological models and test equipment were made compatible. Drawing on empirical material from both papers, Juhl and Bates (2020) then examine and conceptualize collaborative knowledge production in technology development between academic researchers and industrialists more generally – also in a historic context.

The fifth BOAP characteristic is perhaps the most difficult to capture. When Hyysalo et al. state that "[d]ifferent temporalities and spans of change are seen as multiple enacted contexts […and] events are seen as simultaneously constituting and being constituted by broader patterns" (Hyysalo et al. 2019: 7), they are most likely referring to broader patterns *in society*. Although my focus is narrower, I suggest that broader patterns may still be at work in more humble contexts of *engineering or management practice* and that that the fifth BOAP characteristic can be made relevant for these contexts – insofar that they provide "examination of how the structuring elements are present in real-life situations, and in turn, how the situations reshape the structuring elements and what can be learned about the patterns and structures as they are enacted" (ibid). Consider the following anecdote from the case on maturing a novel steering technology (see Chapter 1.4.2). Midway through the project, I distributed copies of Vinck et al. (1996) and discussed its findings with the team. A few weeks later I was on my way to a 'resource meeting' with the BU Engineering Director and the Project Manager who would eventually be tasked with implementing the technology into a product. Before leaving our project room I took a photo of a whiteboard upon which there were notes from an earlier discussion with the team on resource needs. As I was sliding the phone back into my pocket, the Mechanical Hardware Specialist looked up from his computer screen, smiled and said: "Don't let that object commission you".[15] As I suggest in the methodological framework of Chapter 5, technology managers and engineers consistently evaluate and forecast the potential consequences of the technical objects they position across 'multiple enacted contexts'. This is probably related to the findings of Williams and Figueiredo (2014) that *engineering work* "involves constantly looking for workable solutions while coordinating people and linking up heterogeneous pieces of information inside a complex network of interdependencies" (Vinck 2014: k). Chapter 5 therefore argues that *staging with objects* is a practice requiring regular conscious reflection on and with the associations in which one's objects are in/excluded – be these on the shop-floor, in the managing executive's office or at an OEM's R&D department. Here I submit that the *reflective actions* by which technology managers and engineer's successfully *(de)stabilize* these associations are also useful for the dissertation's general methodology. Two points on *staging with objects* which I use to guide reflection on 'different temporalities and spans of change' follow here (Bates 2020a, forthcoming: 131):

- The agency to situate and define objects is a complex process of negotiation and does not reside in a single actor. Objects are reciprocally (de)stabilized by the effects of actors' changing positions as they navigate changing situations.

- Staging with objects requires increased attention to how objects perform across intentional (commissioning) and unpredictable (mediating) roles. This necessitates conscious reflection over how objects are accepted, contested and changed in interaction with different perspectives.

While these points were developed to foster reflective practice in processes of technology development 'on-the-fly', I propose that this same line of thinking can enable the theoretical analysis towards which the fifth characteristic is directed – "where the same moment is analysed in terms of the development of practitioners, practices and the situated enactment of action" Hyysalo et al.2019: 7).

A combination of theory and reflective practice is also applicable to the sixth BOAP characteristic: "Investigate the shaping and shape of technology in the process […] BOAP studies insist on paying attention to materiality" (Hyysalo et al. 2019: 8). Russel (1986: 335) argues that an "explanation of technological change must show not only what different groups think about an artefact, but also […] their differing abilities to influence the outcome of its development and adoption". Two points for

[15] From a conversation on 15 May 2017. Translated from Danish by the author.

guiding reflection on *differing abilities to influence outcomes of development and adoption* can also be extracted from Bates (2020a, forthcoming: 131):

- Attention to processes of staging with objects can help technology managers and engineers articulate and accommodate fluid demands from top management teams who set overarching objectives, exercise control over resources, and provide mandates for action, but are otherwise not involved in solving technical issues in translations from invention to commercialization.

- Viewing ‘commercialization criteria’ as products of ongoing negotiations between diverse actor-networks can provide more effective strategies (*means of action*) than viewing these criteria as stable, punctualized entities that guide how a technology is developed.

The seventh BOAP characteristic is to “[c]reate balanced and empirically adequate accounts of the different actors in the ecology phenomena” (Hyysalo et al. 2019: 8). Drawing on the example from Hyysalo et al. (ibid), my 15 years of experience in DPS provides unique insights into *how*, and by *whom*, “key design decisions are made”. Still, practical experience is no substitute for theoretical reflection. To this end I employ three principles of the sociology of translation as formulated by Callon (1984: 196, my italics): “[T]hose of *agnosticism* (impartiality between actors engaged in controversy), *generalized symmetry* (the commitment to explain conflicting viewpoints in the same terms) and *free association* (the abandonment of all a priori distinctions between the natural and the social)”.

Initially, *agnosticism* was the most difficult to accommodate. According to Callon (ibid: 200), putting this to work necessitates: “No point of view is privileged and no interpretation is censored. The observer does not fix the identity of the implicated actors if this identity is still being negotiated”. My auto-ethnographic role as ‘technology manager’ is certainly *privileged*. Moreover, maturing technologies requires *fixing identities as they are being negotiated* and *censoring* possible (undesirable) outcomes. At the start of the project, it was unclear to which extent the writing process was *de facto* coordinating roles and action within my team(s). Were my hypotheses on associations actually engendering problematizations and enrolments in the development space? To reduce this entanglement, I implemented a six-month delay before reviewing/utilizing any empirical material. According to Law (2009: 145) *generalized symmetry* “shows that, as a necessary part of the experiment [of rearing scallops], fishermen are tamed too”. Extensive *practical* experience in marshalling human and nonhuman actors towards specific ends certainly supplements *theoretical* reflection on symmetrical means by which such ends are realized. Still, I remain vigilant for asymmetrical formulations when editing manuscripts, bearing in mind that *technology development* is also “a web of relations that makes and remakes its components” (ibid: 145). In my own experience, abandoning *a priori* distinctions between the natural and the social is not a leap-of-faith for engineers. The tools of our work, like engineering reports, are amalgamations of associations between human and nonhuman actors (see 'SDP-reports' in Bates and Clausen 2020). Vinck (2009) suggests that engineers are particularly adept at recognizing, positioning and responding to objects that condition conflicting *intentions*. Vinck also proposes that by focusing on technical reality, "a different vision of technology will emerge – a vision that technicians should find easy to understand because it will be based on their day-to-day life" (Vinck 2009: 1). Although my 'day-job' as technology manager and engineer is wholly focused on sociotechnical endeavors, concise formulations of mutually shaping associations can be difficult. I continue to proof-read manuscripts with a focus on clarity.

This brings us to the eighth characteristic of BOAP: "Attend to the detailed dynamics of sociotechnical change both empirically and theoretically" (Hyysalo et al. 2019: 8). This is clearly easier said than done. While my auto-ethnographic role provides a rich source of empirical material, theoretical diligence is not a given. Hyysalo et al. express "dissatisfaction with large bodies of STS studies [in] that they struggle to live up to their own criteria due to their unduly simplistic and limited research designs" (ibid). I return to consider how well I have accommodated this final criterion in the reflections of Chapter 6.

3.4. MAKING SENSE OF (MY) INDUSTRIAL PRACTICE

> It's more than just explaining to [the customer] that we can't give them a prototype just now. We need to communicate that we have technical issues that are only solvable in cooperation […]. This means an open conversation about their vehicle architectures […]. So that we can go back to our laboratories, back to our own test-track and experiments [… and] come back confident that the prototype we do deliver will also function in *their* vehicles at *their* test-track […], according to *common* expectations.

The above quote[16] is from the Work Function (WF) division Director of Technology, and stems from a preparation meeting for a planned visit with the largest *original equipment manufacturer* (OEM) in off-highway mobile, that was organized by the WF Sales Manager (this case is described in: Bates 2020a, forthcoming; Bates 2020b; Bates and Clausen 2020). In addition to the Director of Technology, the Sales Manager and myself, meeting participants included other members of the *technology development project team*, the Product Application Engineering Manager, the Project Manager for the *product development project* that would eventually take over the technology and one of his Engineering Specialists. The scheduled meeting with the OEM was the result of a month-long, meticulous planning process (including emails,

[16] From a meeting held on 11 November 2017. Translated from Danish and edited for brevity and clarity by the author.

tele-conferences, hydraulic diagrams, CAD models and calendars), actualized by the Sales Manager to gain face-to-face access to the OEM Director of R&D. This was the latest in a series of meetings between the OEM and WF to discuss the novel technology. In the previous meeting, the OEM's Director of R&D made clear that they expected a plan-of-action for delivering prototypes prior to any additional meetings. Initially, the intention of the preparation meeting seemed simple: Develop a *plan-of-action* for delivering prototypes to the OEM. Still, as pointed out by the WF Director of Technology, the vehicle architecture, internal and external performance expectations and functional reliability of the prototypes were interconnected in ways which made them difficult, if not impossible to separate. This supposedly simple plan-of-action was *itself a network extending out in time and place* (Law 2009: 142).

This brief vignette, the quote from the WF Technology Director and the sociotechnical composition of the preparation meeting all resonate with the ontological position presented by Callon (2004) in the concept of 'hybrid communities', which he elaborates as follows:

> Talking of community means giving up the myth of the brilliant individual innovator and inventor. It means recognizing that users or consumers who express their preferences are not isolated but caught up in social networks. It is collectives that invent, design, develop and use innovations. In fact, more and more often, the same collectives simultaneously take care of all these activities. In order to do so they combine the competencies of different actors. These collectives also contain technical devices and in particular systems of communication without which they would be ineffective. In short, these strange melting pots are a mix of humans and nonhumans. (ibid: 4).

While the *hybrid communities* concept aptly describes the challenges and opportunities of negotiating industrial practice, the *staging with objects* concept intends to assist practitioners in making sense of these negotiations. The material semiotic tradition from which staging with objects stems is shown adept in exploring the enactment of realities, the *ontological*, as well as describing the making of knowledge, the *epistemological* (Law 2009). However, the innovation management field has been less concerned with the *enactment* of realities than the origin, nature and limits of concepts and tools (see subsection 1.2.1.). To address this paucity, I present a view of *both* ontological and epistemological considerations as intrinsic to any understanding of industrial practice: The *means* technology managers and engineers employ in developing technologies engender realms of (im)possibility within the development space.

The implications of this material semiotic focus culminate in the Methodological Framework for Managing Technology Development presented in Chapter 5 and will be reconsidered in Chapter 6. In the following chapter, empirical material from the two cases is analyzed from the perspectives of SST concepts presented thus far, according to the perceived relevance of these concepts for the research question, and the sub-questions and methodological considerations of this chapter.

4. DISCUSSION

This dissertation poses the question, **how can *staging with objects* contribute to managing technological innovation across specialized knowledge networks** and aims to develop a methodological framework that can assist technology managers and engineers in *staging with objects* as part and parcel of their industrial practice. With outset in three key dimensions of the research question, coupled with findings and conclusions from five papers supporting the dissertation, this chapter provides a theoretical discussion intended to nourish and balance the more practical methodological framework presented in Chapter 5. To these ends, the three key dimensions – **facilitating engagement across specialized networks, fostering common points of reference and alignment of interests across diverse stakeholders, and helping actors to articulate and mobilize resources within their organizations** – are considered individually, before being associated in the summary at the end of the chapter.

4.1. FACILITATING ENGAGEMENT ACROSS SPECIALIZED NETWORKS

Here I consider 'engagement' as the *manifestation* (however brief) of a specific type of persistent action. This persistence is evident in the word's root, 'engage', which means to entangle or entrap, to lock or hold by influence or power, to mesh with, to involve, bind, hire or engross, to enter into contest or battle, to pledge oneself, to do or take part in something, or to give attention to something.[17] I thus view *engagement* as a temporary result in a continuous process of association through which humans and non-humans, actors and objects acquire or lose *agency*. The *degree* to which something or someone is engaged can be difficult to measure in spaces of technology development. Still, because objects both constitute and trace marks of their authors and relations, they bear specific information about the intentions and conditions influencing their migration between specialized networks and how engagement *is*, *was* or *could be* fostered across or within these networks Vinck (2012: 95). For the purposes of this dissertation, I view *facilitating engagement* as analogous with Callon's (1984) second and third 'moments of translation'. The second moment, *interessement*, is "the group of actions by which an entity […] attempts to impose and stabilize the identity of the other actors it defines through its problematization" (ibid: 207-208). The third moment, *enrolment,* represents the means by which entities are locked into specific roles and spokespeople emerge – with mandates defined by and for the devices of interessement and OPP supporting the network(s) of which they are

[17] Merriam-Webster. (n.d.). Engagement. In Merriam-Webster.com dictionary. Retrieved June 16, 2020, from https://www.merriam-webster.com/dictionary/engagement.

a part. These *mandates*, once achieved, are fragile entities. Spokespersons must not only silence sentient actors for which they speak (however temporarily), they must also provide objects otherwise lacking capacity for language with consistent and recognizable *voices* that both reflect and stabilize the intentions these objects bear, across dynamic situations over which spokespersons have varying degrees of control. Providing voices for objects thus requires "continuous adjustments and devices of interessement that are infinitely more sophisticated" than those necessary for silencing human actors (Callon 1984: 216). This is a primary concern behind the *staging with objects* concept, which posits that *objects* are usually (if not exclusively) supporting or performing as the principle *objectives* through which encounters (or *engagements*) between specialized networks are facilitated. Moreover, and perhaps more importantly, I submit that the *cumulative means* by which such objects – Callon calls them *devices of interessement* – are manipulated and situated provide unique opportunities for understanding and addressing engagement within these networks. Put simply, an *object* is often the most cohesive element linking *associations* and acknowledging that objects perform unique functions in (de)stabilizing these associations is a first step in situating these objects towards specific objectives. This dissertation's empirical material provides multiple examples supporting this perception.

One example of an *object* performing as a device of interessement is the 'Technology Readiness Level' (TRL) device considered by Bates and Clausen (2020). In the hands of a skilled practitioner, TRL is shown adept at facilitating engagement across complex networks of actors and objects. Developed by NASA in the 1970s and first published as a 7-point scale by Sadin et al. in 1989, TRL has been termed a "discipline-independent, programmatic figure of merit (FOM) that allows more effective assessment of, and communication regarding the maturity of new technologies" (Mankins, 2009: 1208). As a management tool, TRL seems to have gained traction in industrial settings after Mankins (1995) expanded it to the current 9-point scale that is widely used in government and industry (Olechowski et al. 2015). Still, with few exceptions, mainstream innovation management literature remains focused on how TRL performs as 'a figure of merit' demarcating the *stages* by which project priorities and milestones can be defined, or how TRL can serve as benchmarks for communication at the launch of new technologies. Challenging this simplistic view, Bates and Clausen (2020) provide an empirical account of TRL as a 'provoking dialogic instrument' – better understood as a device for *staging* processes of technological development than as tool for merely documenting *stages* – and demonstrate how, in the hands of a skilled practitioner, TRL performs to *produce agreement* around the objects and actions it mobilizes and the problematizations these engender across and within specialized networks. In order to effectively express (*without reducing*) the complexities of development into a single digit signaling a technology's *readiness*, the TDP Team deployed the TRL device to produce agreement around a diversity of topics. These topics included the relevance of prototypes, test environments and methods of analysis for notions of functionality and reliability which were defined by the Sales team's interactions with a wider market. But TRL device was also deployed to produce agreement around other unforeseen (f)actors and influxes of resources that become necessary for *validating* these negotiated notions of functionality and reliability. Moreover, TRL provided a forum wherein new questions (i.e. *problematizations* fostered through complex interactions) were identified, organized, acted upon or rejected according to the (sometimes conflicting) needs of the different specialized networks. A key finding from this empirical material, is that TRL can be employed to enable 'qualculation – a notion of calculation that includes judgement and focuses on "arrangements that allow calculation (either quantitative or qualitative) and those that make it impossible" (Callon and Muniesa 2005: 1232). While following the TRL device through a technology development project Bates and Clausen (2020) observe that such *qualculations* are "seemingly performed as interconnected and reciprocating *engagements*" (2020: 27, my italics) that both expanded and impeded the *possible* means of action within the development space. Performing as a 'calculative device' to 'circumscribe agencies', 'organize encounters' and 'establish conventions' (Callon and Muniesa 2005), the TRL device was deployed to 'lock' a variety of actors and objects into roles supporting the development space and helped to shape how these distributed roles were centrally defined and coordinated in a complex process of (re)negotiation.

My work with TRL also illustrates the precariousness of the roles that objects might have or sustain. Although the TRL device in Bates and Clausen (2020) was successfully leveraged to facilitate engagement as part and parcel of a one-to-many obligatory passage point – which could be defined as 'the successful technology development project has achieved sufficient readiness' – the *same* TRL device in Bates (2020a) was later relegated to a lesser role when its supposedly stable network of composite elements was *disassociated* in encounters with unexpected market demands. Paradoxically, these demands were themselves engendered through an increased involvement of customers and managers that was closely tied to the high TRL ratings achieved and described in Bates and Clausen (2020).

When the TRL device's *supposedly* stabile network of composite elements was disassociated in Bates (2020a), efforts to re-associate these composite elements and re-stabilize the technology were initiated through a series of *ad hoc* adaptive movements that were focused on stabilizing other key objects. These objects included a 'whitepaper' documenting customer demands, a functional conceptualization known as 'self-alignment' and a preliminary 'business case'. Initially, the *whitepaper* was a manifestation of top management's intentions to leverage high TRL levels and move forward with customer agreements that would support the preliminary *business case*. Surprisingly, customer demands revealed by the whitepaper resituated (assumedly stable) perceptions of the technology's readiness and made the business case – which had hitherto defined what the technology was supposed to accomplish – obsolete. This necessitated a second movement, which "can be summarized as the

TDP and Sales teams' engagement with top management to accommodate the new notions of functionality and reliability fostered by deeper engagement with OEMs" (Bates 2020a, forthcoming: 187) – as these were revealed in the whitepaper. Contrary to the intentions of top management to stabilize (*close*) the business case, the whitepaper's findings made it necessary to *re-open* the business case and re-define many of the elements of which it was comprised. By re-considering the working principles and steering characteristics that had hitherto driven the project, the TDP Team were able to manipulate these principles and characteristics and ultimately accommodate the unexpected needs of the OEMs. This was accomplished via the recontextualization of a functional principle (*self-alignment*) which provided a *means* for the TDP Team to re-open the punctualized networks supporting the technology's established *readiness levels.* Because these re-opened networks shared underlying components with the preliminary business case, the TDP Team was able to simultaneously adjust the TRL device and business case and eventually *re-define* the technology in ways that addressed the destabilizing aspects of new market demands. A variety of interdependent objects were thus *staged* (i.e. manipulated, situated and ultimately (re)associated) to facilitate engagement, in ways that would be impossible if these objects were treated as isolated or black-boxed entities. I say *impossible* because 'staging with objects' is focused on strengthening *associations* and fundamental associations between these objects had been severed – paradoxically *through* the customer interactions meant to strengthen them. To *re-establish* the severed associations, the TDP Team *re-opened* these objects and in an impressive display of technical acuity, were able to *re-define* and *re-adjust* the shared components of which the objects were comprised. A principle finding that can be drawn from Bates (2020a) is that epistemological considerations – regarding the *means* by which technology managers and engineers can know or act – are inseparable from ontological considerations about how things are manifested and associated. Plainly stated, *how* engagement can be facilitated in spaces of technology development is itself an intricate *association* of diverse, composite objects and the objectives they engender. This ANT inspired view is also apparent in another paper supporting this dissertation: Bates (2020b).

The case considered in Bates (2020b) takes place between the activities described in Bates and Clausen (2020) and Bates (2020a, forthcoming). Here, the TRL device and *new product development* (NPD) process model into which it was intended to feed were only peripherally involved in how actors and actions necessary for *achieving* the functionality and reliability of a novel technology were being facilitated – despite the TRL device and NPD process model being well-integrated into the company's formalized decision-making processes. TRL and NPD devices certainly played key roles in defining specific *demands* from which decisions would be made (*readiness levels* and *milestones,* respectively), but another *device of interessement,* proved necessary when the development group began to consider the technically complex work arrangements through which these *levels* and *milestones* could be achieved. To this end, the development group drew on a series of patents to facilitate engagement around the ‘equipping’ of an interim functional conceptualization of the technology. According to Vinck (2011: 25), “*equipping work* is the collective activity that involves agreeing about the features to be added to intermediary objects so that they can be enrolled in the space of exchange between actors”. Because the hydraulic patents of Bates (2020b) concisely and unambiguously defined *precise* orders of functions for the technology being developed – without otherwise limiting how the individual functions were realized – these could be situated by the development group as the *objects* by, and for, which preliminary *objectives* were defined. The patents thus made it possible for the development group to circumscribe, configure and coordinate work arrangements that supported their development objectives. Practically, this was achieved piecewise. First through plenary sessions where the group considered *what* the patents were expected to accomplish *from a purely technical perspective* so they could define work arrangements that would manifest and validate these technicalities. The group then placed the patents at the *intersections* of these work arrangements – where results from each arrangement were compared and evaluated according to how well the patents’ precise orders of functions performed *across* these arrangements. Thus, a variety of distributed and iterative *actions*, spanning prototype designs, simulations, laboratory tests and in situ vehicle tests, could be facilitated and (perhaps more importantly) made relevant for one another from a centralized position.

In summary, ‘facilitating engagement across specialized networks’ requires more than rallying participants around common objectives (e.g. readiness levels or milestones) as these are defined via conventional management tools. Rather, *facilitating engagement* is better viewed as a practice by which *conditions for alignment* are being prepared through attentive processes of making associations relevant. Because objects both constitute and trace marks of their authors and relations – while gaining or losing momentum through the intentions and conditions of their migration – careful attention to the roles objects play in establishing and stabilizing associations is a key element of this practice. This is easier said than done. As Vinck posits, “the analysis of technical objects is balanced between the denunciation of underlying sociological mechanisms and the recognition of intrinsic technical efficiency” (Vinck 2009: 213-214). But technology managers and engineers must navigate this balance in *real time* while ‘working-on-the-fly’ with incomplete knowledge. From the cases reviewed here, I submit that ‘technical acuity’ was important in how participants identified and responded to this complex comingling of the social and technical. That detailed knowledge of the sociotechnical networks of which their objects are comprised supports engineers in (re)directing the objects to novel ends will perhaps seem banal to STS scholars. Still, it is important to consider that *engagements* in industrial technology development projects are often *instigated* through decision-making tools (like NPD process models or the TRL figure of merit) which take for granted that technical competencies and insights are readily available for selection, promotion and control (Clausen and Yoshinaka 2009). In counterpoint, these cases demonstrate that other objects – as embodiments of *technical acuity* – facilitate action through mediation and coordination. As an introduction to the next subsection, one could also add, that the objects of our attention must *concurrently* support common points of reference across the variety of interests that propagate a development space, if they are to be successful.

4.2. FOSTERING COMMON POINTS OF REFERENCE AND ALIGNMENT OF INTERESTS ACROSS DIVERSE STAKEHOLDERS

Once engagement across specialized networks is achieved (however provisionally), it must be maintained and continuously adapted', usually in association with parameters that are only partially defined or considered. Establishing common points of reference and alignment of interests play an important role in this endeavor as this enables stakeholders to define and prioritize complex infrastructures of objects and work arrangements. Without them, notions of *what* is relevant and *how* this relevance can be maintained (what Latour calls *matters of concern* – see Chapter 2.2) become difficult, if not impossible.

To these ends Bates and Juhl (2020, forthcoming) introduce 'referential alignment' to depict these associations. It is a term "develop[ed] to characterize how knowledge artefacts and processes refer back and forth between different material, organizational, local and temporal settings. The paper by Bates and Juhl (2020) also invokes the staging metaphor to sensitize towards the ongoing work required for participants to successfully constitute, configure and transform (*stage*, per Clausen and Yoshinaka 2009) diverse material and epistemic conditions. Through these efforts, those involved are able to create and maintain a referential infrastructure across different situated settings that can support common points of reference and alignment of interest amongst the different stakeholders. The paper also draws on Vinck (2011) to consider the 'equipping of intermediary objects' and how this shapes collective work. Here, the focus ís on the upstream constitution and configuration of an 'intermediary object' to perform as a 'boundary object' (that is considered a referential infrastructure) as its comparability and commensurability were shaped across diverse stakeholders. Bates and Juhl (2020) show that an intermediary object (the test rig) was initially staged as an OPP to support translation and alignment. Through this process of *constituting* a preliminary establishment of involved interests, and *configuring* – through new knowledge production and the translation of this knowledge into a reference construction and alignment of material conditions – the test setup represents a way to *transform* intermediary objects into boundary objects. Following this process of 'referential alignment' across actors and objects, meetings and experiments in Denmark and Sweden, Bates and Juhl demonstrate the careful orchestration of a 'test-setup' (as well as the collaborative environment necessary for their undertaking) through which the negotiation and coordination of normative expectations and performance criteria are staged in order to define a shared space for the different collaborators. Considering the test setup as it was initially assembled to validate a novel hydraulic lubricant and was later expanded to further develop the lubricant, Bates and Juhl describe the test setup as being more than a *means* of achieving specific ends, to illuminate how the test setup simultaneously performs as both an *object of* and an *objective for* the collaboration – via ongoing negotiations and interpretations around different articulations of functionality and reliability. As a key object, the test setup was critical in connecting the partners around 'common performance criteria' that were established early in the collaboration. Later, the test setup engendered unexpected results that performed to undermine the collaboration, making it necessary to *re-stage* the network of partners and resources (including the setup) around a new problem definition and new objectives. As it became apparent to the collaborators that the novel lubricant could not be easily validated in ways that would make it relevant for the hydraulic market, which the industrial partner represented, the collaborators' intentions were redefined and ultimately realigned with a new theoretical problem the academic partner excelled at solving – as opposed to the initial and more practical demonstration problem for which the industrial partner was originally approached for assistance.

Whereas Bates and Juhl (2020) focus on practical concerns of *staging* referential alignment in industrial-academic collaboration, the paper by Juhl and Bates (2020) attempts to conceptualize 'referential alignment' in ways that account for the mechanism through which knowledge and technology is made transferable in collaborative innovation. To this end, Juhl and Bates draw on Haraway's (1988/2007) 'situated knowledges', which addresses the importance of the locally and temporally situated positions from which knowledge is produced and qualified, to consider how relations between 'key knowledge artifacts' from the case were circumscribed and made relevant for both the *specific* and *common* needs of the academic scientists and industrial engineers. According to Haraway (1988/2007), acknowledging the *contingencies* of the subjects' own position in the world *enables* possibility for greater objectivity than claims to be a neutral observer possessing a perspective from 'nowhere' and ignoring the exigencies shaping perspectives. This is particularly relevant for cases of collaboration between partners in different organizations and it is exemplified in the industrial academic collaboration to adapt and validate the novel lubricant. Here contingencies of the industrial market to which the lubricant was being adapted were only revealed piecewise as results of novel interactions which the collaborators arranged between 'key knowledge artifacts' that could only be *objectively* understood as tailored associations between the scientific field of tribology and the industrial market. In this manner, the collaborators' rationalizations around with and for these artifacts performed dual roles: "The act of making rational, of ordering. And the act of pasting coherence on after the event" (ibid: 171). This complex sensemaking process was further confounded by the fact that possible *means* by which the novel lubricant could be tuned to accommodate these practical exigencies took root in 'scientific standards' developed by and for the scientific field of tribology. According to Cartwright (1999), the world needs to be manipulated to produce the order that we know as physical laws. An arrangement that produces this sort of manipulation is what Cartwright terms 'nomological machine' which is "a fixed (enough) arrangement of components, or factors, with stable (enough) capacities that in the right sort of stable (enough) environment will, with repeated operation, give rise to the kind of regular behavior that we represent in our scientific laws" (Cartwright 1999: 50). As if this endeavor were not complicated enough, these *repeated operations* needed to accommodate industrial standards which had evolved with the hydraulic lubricant that the novel lubricant was intended to replace. Paradoxically, the collaborators needed to validate the novel lubricant through industrial standards that were not wholly separable from the behaviors of the dominant lubricant. To analyze these complex associations Juhl and Bates (2020) draw on Barad's (2003) *performative philosophy apparatuses*, which are 'material discursive' insofar as they produce determinate meanings and material beings that *exclude* the production of others. Based on the idea of 'agential realism,' Barad sees the universe as comprised of phenomena, which she defines on the basis of 'ontological inseparability of intra-acting agencies'. To Barad, objects and phenomena emerge through particular intra-actions. Similar to Cartwright, Barad argues that phenomena are produced by apparatuses, for example laboratory installations like the test setup described earlier. According to Barad (2003: 816):

> Apparatuses are not inscription devices, scientific instruments set in plane before the action happens […] Apparatuses are not static arrangements *in the world, but rather apparatuses are dynamic (re)configurations of the world, specific agential practices/intra-actions/performances through which specific exclusionary boundaries are enacted* […] Apparatuses are open-ended practices.

Through an empirical account of collaborators working to make a variety of apparatuses relevant in novel contexts, Juhl and Bates (2020) consider how distributed knowledge production performs to establish referential infrastructures that enable production of coherent and applicable results across different situated practices. An important finding was the dogged work necessary to align the material conditions of key knowledge artefacts so these could be made commensurable across the needs of the industrial engineers and tribology scientists. Here, the transformation of each knowledge artefact (to meet the exigencies of the other artefacts) required that these artifacts simultaneously maintained relevance for, and semblance to, their principle intentions.

In summary, 'fostering common points of reference and alignment of interests across diverse stakeholders' can be summarized as a process of 'referential alignment' Drawing on empirical material from the same case, Bates and Juhl (2020), and Juhl and Bates (2020) are separate attempts to illuminate different aspects of this complex process. Within this process, Bates and Juhl (2020) illustrate that *staging* can be viewed as a strategy of developing *boundary objects* through which a diversity of methods and criteria from different social worlds can be coordinated and made comparable and commensurable. To these ends, the concept of *equipping* intermediary objects to perform as boundary objects seems to provide a *means* by which industrial practitioners can identify and develop the qualities or identities of objects that make this comparability and commensurability possible. Juhl and Bates (2020) demonstrate that when observations deviate from the expected, observers must readjust and expand their gaze from their intentions with these objects (apparatuses), to the material *intra-action* between these objects. Referential alignment thus becomes a process of aligning material configurations in order to ensure that observations produced in one setting can be reproduced and understood in other settings. How practitioners address local specificities within these settings thus becomes a material condition for how they understand knowledge (i.e. the facts these specificities generate) and the conditions for its applicability.

4.3. HELPING ACTORS TO ARTICULATE AND MOBILIZE RESOURCES WITHIN THEIR ORGANIZATIONS

In technology development, mobilization of resources is closely tied to the ways by which knowledge is configured, stabilized and facilitated across a variety of actors and objects through organized encounters spanning diverse stakeholders (see Clausen and Yoshinaka 2009; Vinck 2012, 2014; Yoshinaka and Clausen 2020, forthcoming). Drawing on Callon (1984), I define ‘mobilization’ as the *actualization of a mandate* (however temporary) which has been established through a process of *problematization*, *interessement* and *enrolment* that must be in place before an objective can be realized. Put simply, a *mandate* is the articulation of an assumedly stable network of heterogeneous elements that have been assembled to support a specific, supposedly achievable, objective. In technology development a single objective may require a multitude of specific mandates, achieved through different *problematizations*, *devices of interessement* and *enrolments* across a variety of networks. The broad *objective* to ‘validate a novel lubricant for the off-highway mobile industry’ is certainly the most complex example in this dissertation (Bates and Juhl 2020), where different mandates included jurisdiction (however temporary or limited) over people, processes, equipment and interpretations of standards. Still, it is important to note, that although mandates may be finite, the ways by which articulations of resources can serve to impede or achieve the objectives they are formulated to support are inherently more difficult to delineate. Often, the limitations of an assumedly stable mandate are revealed through spokespersons’ initial attempts to mobilize the mandate. Here, a problem is identified, interests are stimulated, and entities are enrolled to articulate the *material needs* of an established network, but its eventual mobilization reveals the problem, interests or roles of which the articulation is comprised to be incongruous with the *materials* they were intended to support. Empirical material supporting this dissertation includes at least one example of how mandates intended to support the material needs of a network were transformed at their point of mobilization and were necessarily rearticulated. This is important because it demonstrates that abilities to articulate and mobilize resources do not reside in a single actor but develop as a matter of negotiation across shifting (f)actors as objects are reciprocally (de)stabilized by the effects of changing positions as actors navigate changing situations (see Bates 2020a, forthcoming).

Considering a transition from invention to commercialization as a ‘messy processes of interwoven translation’, Bates (2020a, forthcoming) emphasizes the reciprocal nature of what actors do with objects as they are circulated, and characterizes such translations as dependent on how actors can respond to ‘possible means of action’ by leveraging technical acuity to identify and connect with objects that are already in circulation. In this case, transitioning from a technology development project (TDP) to a product development project (PDP) required that TDP, PDP and Sales Teams acquire specific technical information about the present and future vehicle architectures that defined the market for which they were designing. In addition to internal alignments between the TDP and Sales teams and top management, acquiring this information would require specific commitments between the company and principle customers, where these commitments were expected to take root in technology *readiness assessments* (TRA) and a preliminary *Business Case* made by the company. To this end, the TRA and Business Case were mobilized with intentions to secure the missing knowledge and develop a ‘whitepaper’ which could describe preliminary ‘pilot customer considerations’ for top managers in the company. In this manner, the resource objectives associated with these objects and actors were twofold: 1) to secure (external) knowledge on customer vehicle architectures; and 2) to justify retention and expansion of (internal) resources for continuing the transition from invention to commercialization according to the demands of a company sanctioned NPD process model. Here, the second objective, as it was executed by the TDP and Sales teams, was wholly dependent on the successful mobilization of the first, which was initiated by top management. Unexpectedly, the mobilization to acquire these resources performed to destabilize both the objects supporting the mobilization and the networks of which these objects were comprised. Although the *acquisition* of technical knowledge about present and planned vehicle architectures was a success, the information was not directly employable in the context it was intended to serve. Both the technology’s *readiness* and the Business Case were destabilized. *Re-stabilization* necessitated that their underlying networks be ‘reopened’ and transformed by the TDP Team in ways that would make *previous* work arrangements and their elements relevant for the *new* elements brought into the development space. This brief vignette demonstrates that ‘helping actors to articulate and mobilize resources within their organizations’ is more than assisting them in the successful acquisition of resources. On the contrary, as Latour (1987: 233) posits, “the very success of the mobilization, the very quality of the instruments, will have as its first consequence their drowning in a flood of inscriptions and specimens”. Consequently, *ideal* articulations and mobilizations of resources would encompass ways to retain the stability of as many elements as possible within the development space while still being able to manage them (see Latour 1987: 237).

An empirical example of work arrangements *closer* to Latour's ideal can be seen in the paper by Bates and Clausen (2020). To achieve a higher TRL rating required by the company sanctioned NPD process model, ambiguous performance results between prototypes tested in laboratory experiments and vehicle tests at the company test-track needed to be understood and addressed. To these ends, the TDP Team required specialized knowledge from additional technical specialists, hailing from two different departments in the firm, as well as changes to laboratory equipment which could accommodate this knowledge. Whereas the *information resource* acquired by the TDP Team in Bates (2020a, forthcoming) required that *assumedly stable* key elements of the development space be transformed to accommodate new findings, it was the *known instability* of key objects within the development space that fostered the articulation and mobilization of resources in Bates and Clausen (2020). That the TRL device and the technology being developed were allowed to be renegotiated and transformed in every TRL Assessment, made it possible for the TDP Team to identify and carefully consider how any necessary and new *elements* brought into the development space could contribute to stabilizing other elements of the technology *before* they were brought into the development space. These circumstances were fundamentally different than the resource infusion described in Bates (2020a, forthcoming), where articulations and mobilizations supporting the acquisition of knowledge took root in assumptions about the technology's *achieved* stability and were brought into the space without considering their possible effects on other elements.

Despite these differences, the articulation and mobilization of resources in both cases was closely tied to the TRL device – where it was the TDP Team who leveraged the device towards the acquisition of what they ascertained as necessary resources in Bates and Clausen (2020), and top management who took control of the device in Bates (2020a) to push new and necessary knowledge into the development space. In the first example, the TDP Team managed to keep the technology 'open' long enough to peer into its inner workings and provide top management with a list of requirements (*elements*) for *black-boxing* it later. In the second example, top management leveraged the high (assumedly stable) TRL scores as a 'black-box' to bring new knowledge into the development space, forcing the TDP Team to re-open other closed networks to accommodate the new knowledge and make it relevant for the development space. Both examples underline issues of temporality when considering the (in)stability of networks as new elements come into play. A key takeaway seems to be that the articulation and mobilization of resources necessitates conscious reflection over how objects are accepted, contested and changed in interaction with different perspectives. Interestingly, the *means* by which technology managers and engineers successfully handled requested (Bates and Clausen 2020) and compelled (Bates 2020a, forthcoming) *resource* infusions were rooted in (technical) abilities to identify and manipulate *key objects* playing principle roles across multiple networks.

4.4. SUMMARY OF CHAPTER 4

This chapter discusses the three dimensions of how *staging with objects* can contribute to managing processes of technology development according to empirical material spanning five papers (Bates 2020a, forthcoming; Bates 2020b; Bates and Clausen 2020; Bates and Juhl 2020, forthcoming; Juhl and Bates 2020). Although each dimension is considered individually, it is important to note that these are mutually shaping aspects of an entangled process of 'constituting, configuring and transforming' (*staging*, see Clausen and Yoshinaka 2009) complex networks of actors and objects with shifting degrees of agency. Neither are these dimensions meant to be understood as sequential parts of a mechanistic process with clear start and end gates. For example, common points of reference and the successful articulation of resources can be strong partners in facilitating engagement, just as the means by which engagement is facilitated can both expand and limit possibilities for aligning interest across diverse stakeholders, or how resources can be mobilized within a specific organization. Moreover, the relevance of the objects and work arrangements taken from the empirical material as examples are not limited to the scope of a single discussion for any individual dimension. To demonstrate that the same case can empirically support any one of the key dimensions, I combine empirical material and examples from this chapter when presenting the key elements in the methodological framework presented in the next chapter. Before proceeding, some general takeaways and reflections from this chapter are :

- Much of the innovation management literature reviewed in Chapter 1.2 views *commercialization criteria* – particularly as they are defined in company sanctioned process models and figures of merit – as stable, punctualized entities guiding how a technology is developed. In contrast, the dissertation's empirical material suggests that viewing such criteria as products of ongoing negotiations between diverse actor-networks can provide more effective strategies (means of action) for managing processes of technology development.

- The agency to situate and define objects is a complex process of negotiation and does not reside in a single actor. The positions of actors and their objects are reciprocally altered as they re-positioned to navigate changing situations. This necessitates conscious reflection over how objects are accepted, contested and changed in interaction with different perspectives (Bates 2020a, forthcoming).

- Keeping objects *open* – not 'black-boxing' them prematurely – seems to support all three of the key dimensions. Still, the challenges of this endeavor should not be underestimated. Stable black-boxed entities can migrate between networks in ways that instable entities cannot. Moreover, expressing the complexities of technology development into single digit or milestone (á la TRL, or NPD process models) enables a diversity of stakeholders to make agreements about a technology without necessarily understanding the *complex technicalities* upon which it rests. Perhaps a focus on the *production of agreement*s stabilizing these digits or milestones – as opposed to a relentless pursuit of *stable* digits and milestones for pacing industrial technology development – can foster incentives for keeping objects open?

- Decision-making tools (like NPD process models or the TRL figure of merit) take for granted that technical competencies and insights are readily available for selection, promotion and control. Such assumptions downplay the role of 'technical acuity', which enabled case participants to *re-open* 'closed objects' – and ultimately *re-define* and *re-adjust* the shared components of which the objects were comprised – when faced with the de-stabilization of, or disassociation between, principle objects (Bates 2020b).

- Whereas top management teams may set overarching objectives, wield control over resources, and define mandates for action, they remain on the periphery of how technical issues in translations from invention to commercialization are solved. Moving beyond top-level strategizing, staging with objects shifts focus to the *technical acuity* and micro-processes necessary for technology managers and engineers to articulate and accommodate the fluid demands fostered by top management's peripheral involvement in the development space (Bates 2020a, forthcoming).

5. A METHODOLOGICAL FRAMEWORK FOR MANAGING TECHNOLOGY DEVELOPMENT IN INDUSTRY

The intentions of this dissertation are twofold. The first intention is a largely academic endeavor, drawing on SST theory and practice in an auto-ethnographic study to expand a mostly prescriptive body of 'innovation management' scholarship – which purports to service industrial managers and engineers through limited observations, interviews and interventions – to include the first-hand experiences of a skilled practitioner with responsibility for the translation of technologies from invention to commercialization in industrial contexts. The second intention repositions findings from these academic endeavors towards more practical ends: A methodological framework addressing how objects can be staged by technology managers and engineers to support the processes of industrial technology development to which they are employed. Whereas the first intention dominates the preceding chapters, this chapter is engaged with the results of the second and its language and framings reflect this practical motivation. The chapter begins with an introduction to how technology development can be perceived as a sum of continuously generated effects of networks of associations. I then present conceptualizations of objects as being useful for identifying, understanding, establishing and/or maintaining different types of associations to support practical endeavors. This is followed by a discussion on how reflective practice, with a general outset in a *perception of associations* and a specific focus on how *staging with objects* within these associations can assist technology managers and engineers in understanding and executing their work arrangements. The chapter concludes with a glossary of concepts from the preceding subsections.

It is important to note, that this chapter is intended to 'stand-alone', so it can be presented to practitioners occupied with industrial technology development without their needing to read the dissertation's other chapters. Thus, its structure (particularly the footnotes) is different from the other chapters and certain topics are repeated.

5.1. TECHNOLOGY DEVELOPMENT AS A NETWORK OF RELATIONS

This chapter presents a methodological framework focusing on how *staging with objects* can supplement three key dimensions of transitioning technologies from invention to commercialization that I emphasized in chapter four:

1. Facilitating engagement across specialized networks
2. Fostering common points of reference and alignment of interests across diverse stakeholders, and
3. Helping actors to articulate and mobilize resources within their organizations.

Although these dimensions are considered individually, they are mutually shaping aspects of the development space with reciprocal effects. Before returning to these dimensions, note that this framework differs from other frameworks or process models that technology managers and engineers may be familiar with from previous encounters with 'innovation' or 'management' literature. This framework is not another flowchart, process model or recipe for achieving "successful technology development". Neither does it provide a 'be-all' template for managing innovation. Rather, the framework intends to provide *means* by which skilled technology managers and engineers who find themselves (in)voluntarily organized towards (un)specific objectives can hone their abilities as *reflective practitioners* in real-time within the limitations and opportunities provided by their industrial practice.

Understanding the implications of this framework thus requires brief introductions to two fields of philosophy and a theoretical and methodological approach to the social sciences. The first of these fields is concerned with *the nature of reality*: 'Ontology' is a combination of the Greek *ontos* (being) and *logos* (logical discourse). For purposes here, it is sufficient to say that *ontology* is "concerned with the nature and relations of being".[18] The second field of study is concerned with *the nature of knowing*: 'Epistemology' is a combination of the Greek *epistēmē* (knowledge) and *logos* (logical discourse). Simply put, *epistemology* is concerned with "the nature and grounds of knowledge especially with reference to its limits and validity".[19]

Most innovation and management literature limits itself to questions of epistemology – how do managers and engineers obtain knowledge and leverage this knowledge in action? – and rarely addresses ontology. Questions regarding the nature of reality are mostly considered tangentially – what 'good' *management* or *innovation* are, or provide, in assumedly transparent contexts – if at all. In contrast, the methodological framework presented here takes root in the assumption that epistemological considerations – regarding the *means* by which technology managers and engineers can know or act – are inseparable from ontological considerations about how things are manifested and associated. Actor-network theory (ANT) provides a means for understanding both. In my experience, the basic tenets of ANT are easily grasped by

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[18] Merriam-Webster. (n.d.). Ontology. In Merriam-Webster.com dictionary. Retrieved May 23, 2020, from https://www.merriam-webster.com/dictionary/ontology.

[19] Merriam-Webster. (n.d.). Epistemology. In Merriam-Webster.com dictionary. Retrieved May 23, 2020, from https://www.merriam-webster.com/dictionary/epistemology.

technology managers and engineers. Drawing on the work of John Law and Bruno Latour, these tenets can be summarized as follows. a) The ability to compel action, *agency,* is shared by human and non-human agents (*actors*); b) Agency emerges as a property of associations between *networks* of heterogeneous elements and how these are situated in relation to other *networks* of elements; c) Understanding these networks requires the abandonment of distinctions between the ‘social’ and the ‘technical’ (united in the term *sociotechnical* hereafter): “*Everything* [with]in the social and natural worlds [is] a continuously generated effect of the webs of relations within which they are located”.[20] Some mundane examples of these tenets include:

a) The overhead projector in the meeting room had a VGA cable instead of a HDMI cable forcing participants to gather around the project leader’s laptop to view his presentation
b) To successfully *facilitate* the intentions of its authors, a component specification should meet multiple requirements simultaneously – the specification’s tolerances must match the capabilities of the factory’s manufacturing equipment, be measurable on the factory’s quality equipment and be unambiguously interpreted by the users of this equipment
c) In experiments designed to validate a principle component in a product, a secondary component failed unexpectedly, making it necessary to redesign the validation process for the principle component in cooperation with experts in the secondary component’s functionality and reliability.

These simple examples not only illustrate tangible enactments of relations, they also indicate that a focus on how such relations are enacted can help to describe the associations through which *agency* arises – often unexpectedly and not always intentionally. In this way ANT is not a theory in any traditional sense. Rather than considering *why* things happen (i.e. providing *foundational* proofs), ANT is a *descriptive* endeavor for explaining *how* relations assemble – or don’t. Returning to Law, ANT is not a theory, but “a disparate family of material-semiotic tools, sensibilities, and methods of analysis” that overlaps with other intellectual traditions. What these traditions share, is an idea that *agency* is determined through a network of associations where the *means* by which an inanimate *object* can rise to the position of an *actor* that compels action, or by which the position of a previously *compelling* actor is displaced, are wholly dependent upon their relations across and within a diversity of networks.

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[20] The citaions on this page are from the book chapter by Law (2009: 141, my italics), *Actor Network Theory and Material Semiotics*. For further reading, the book by Latour (2005), *Reassembling the Social*, provides, in my opinion, the most comprehensive and comprehensible introduction to the ANT perceptions applied here. Unless otherwise mentioned, this chapter’s descriptions of ANT are rooted in my own interpretations of these two texts according to my practical experience with industrial technology development.

This network perception is interesting because it allows associations to be viewed independently of the intentions of the individual actors who are directly or indirectly cooperating to support them. In this sense 'cooperation' does not always require explicit agreements for cooperating – or even knowledge of other collaborators' actions. Cooperation simply requires that distributed or centralized action affects the stability of a particular network to the advantage of multiple actors – even when these actions simultaneously affect, often unintentionally, the stability of any *other* networks of which the collaborators are a part. Consider the following *unaligned* cooperation. In their attempts to win market share, competing companies operating in the same market may pursue independent initiatives to accommodate new demands for their products. Still, and despite any principle intentions, these unaligned initiatives may also serve to strengthen growth areas in the general market in which these companies operate. A recent example from the off-highway mobile market is the widespread implementation of new seal types that can tolerate an increasing number of plant-based lubricants. These bio-lubricants proliferate through subsidized environmental initiatives, but they also possess different chemical properties than their petroleum-based counterparts which makes them incompatible with the most widespread seal types used in the hydraulic industry. By independently re-engineering their hydraulic products, with intentions to strengthen their own positions as reliable suppliers to the market in which they operate, competing companies simultaneously strengthen and maintain the *relevancy* of hydraulic products within an expanding area of the general market that might alternatively diverge towards other technologies. The same *means* (i.e. implementing bio-lubricant tolerant seals into hydraulic products to meet novel market demands) influence multiple associations within a larger network. The companies compete in the first association and cooperate in the second, however unintentionally. In ANT, this general process by which networks of associations are shaped or stabilized is called 'translation'. According to John Law, "To translate is to make two words equivalent. But since no two words are equivalent, translation also implies betrayal: *traduction, trahison*". This makes translation a fragile process of relating, defining and ordering objects and actors – human and otherwise.

One of ANT's primary architects, the engineer and sociologist Michal Callon[21], divides the process of translation into four phases, or *moments*. Descriptions of these moments were taken from Chapter 2 of this dissertation have been revised for clarity here. The first moment of translation is 'problematization', "to define a series of actors and the obstacles which prevent them from attaining the goals or objectives that have been imputed to them". For a problematization to be successful, the interests of actors must be piqued. To stabilize any network, however temporary, an 'Obligatory Passage Point' (OPP) around which the goals of diverse entities can coalesce, must be established. An OPP is not itself a moment of translation, but rather a characteristic

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[21] All the citations in this paragraph stem from Callon's seminal article from 1984, Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay.

of the conditions that define a network. Simply put, an OPP is the situation that must occur for any network to manifest, persist or desist. Only through such conditions can the second moment, 'interessement', come into play. Callon defines interessement as "the group of actions by which an entity […] attempts to impose and stabilize the identity of the other actors it defines through its problematization". These entities can include a technology manager, a team of engineers, or the sponsors of a development project. The cumulative result of a successful interessement is the third moment: 'Enrolment'. It is here that entities are locked into specific roles and spokespeople emerge – with mandates defined by and for the devices of interessement and OPP supporting the network. The fourth moment, 'mobilization', can be seen as the actualization of established mandates. "To mobilize, as the word indicates, is to render entities mobile which were not so beforehand". Mobilization is per definition instable. Dynamic entities change and become displaced. New problematizations arise. Consequently, decisions occurring within a network must meet a double requirement: Adding or subtracting elements should render each new displacement easier while *also* establishing, displacing or maintaining associations between principle elements.

This philosophical perception, of everything in the natural and social worlds as generated effects of webs of relations, has important practical implications. By drawing on ANT perspectives, technology management can be addressed as a process of identifying, defining, manifesting and maintaining dynamic associations across, between and within complex networks of heterogeneous elements. Below are some common questions from technology development projects that support these actions.

A. Aspects of the technology need to be identified. In which general market will it compete, what it will deliver that is valuable for this market, etc.?
B. These aspects must then be defined. What are the market's specific demands to the technology (size, shape, performance, cost), how will 'what' it delivers be accomplished, how will its performance be evaluated and validated, etc.?
C. These aspects of the technology must be manifested. How or where will its components be produced, where will the raw materials come from, etc.?
D. Finally, associations between points A. to C. must be maintained. How can the elements holding these associations together be arranged or replaced to accommodate new or desirable configurations of associations – albeit at the risk of destabilizing *other* associations?

With these considerations in mind, the framework presented here intends to sensitize attention towards how objects and actors can be positioned in ways that support the associations that are necessary for achieving the goals for which technology development teams are constituted. The following subsection presents four conceptualizations of objects – characterizing their general intentions and how such objects shape or are shaped within different networks of relations. Here it is important to note that while I differentiate between conceptualizations according to the definitions and intentions of their architects, I do not differentiate between 'objects' and 'devices' (or 'instruments' 'models' and 'tools'). In the confines of this framework, an object's materiality is rooted in action, "not from a sense of prefabricated stuff or 'thing'-ness"[22]. Moreover, 'objects' can also be concepts.[23] Although the architects of the objects considered here may designate a concept as an *object* or a *device* and I respect these designations when referring to them, I use *object* as a common designation for both. For the purposes of this dissertation, *staging with objects* is equivalent to *staging with devices* (or *instruments, models* and *tools*).

5.2. CONCEPTS OF OBJECTS FOR *STAGING* NETWORKS OF RELATIONS

This section is concerned with concepts of objects which I have found useful for identifying, understanding, establishing and/or maintaining different types of associations in my own practice as a technology manager and engineer tasked with moving technologies from invention to commercialization.

5.2.1. BOUNDARY OBJECTS

The concept of 'boundary objects' is designed to consider "the flow of objects and concepts through [a] network of participating allies and social worlds" and is focused on understanding processes of management occurring across these allies and worlds.[24] Boundary objects (BO) are special because they must simultaneously adapt to the local contexts, constraints and exigencies of the different parties using them while maintain a common identity across different sites. Put simply, a BO sits at the *intersections* of different social worlds where it must remain applicable and recognizable across multiple sites of utilization.

An example of a BO is a standard allowing actors to work independently of one another and still be able to cooperate. As one of many widespread standards used for dimensioning interfaces, the American National Standard for Involute Splines (ANS B92.1-1970) performs as a BO to ensure that independent and distributed work arrangements can take place without concerns for their future compatibility. This makes it possible to develop novel technologies that are compatible across and within

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[22] For more on this perception of objects, see the article by Star (2010). *This is Not a Boundary Object: Reflections on the Origin of a Concept*.

[23] In his book, *The Sociology of Scientific Work,* Vinck (2010) proposes that: "Conceptual work involves a broad material exercise in writing, correction, deletion and rewriting, on paper, on the board and on computer. Some of the 'abstract' work can, therefore, be entered in its materiality" – see page 202.

[24] See the article by Star and Griesemer (1989), *Institutional ecology, translations and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology*.

diverse mechanical systems – be these designed around combustible engines, hydraulic components or electrical motors for the mining, marine or manufacturing markets. But the standard also enables an *original equipment manufacturer* (OEM) to switch relatively seamlessly between the product portfolios of different manufacturers. By standardizing mechanical interfaces, the boundary object limits the necessity for different social worlds to communicate directly with one another about these interfaces regardless of their novelty. In this example 'social worlds' could be all the different markets the ANS B92.1-1970 standard serves, the different OEMs from a specific market (like the off-highway mobile industry), or different corporate functions within a single OEM (like Finance, Procurement, Quality, R&D and Sales).

One can say a BO acquires stability by remaining flexible. It is this quality that allows BOs to retain relevance across diverse scenarios of utilization. The ANS B92.1-1070 standard *precisely* defines the form and fit of splines but it is not concerned with how, or from what material, the splines are fashioned. An architect of the BO concept, Susan Leigh Star, characterizes a BO as a set of work arrangements that are both tangible (*material*) and operational (*processual*). [22 above] This makes a BO particularly useful as an object for fostering common points of reference and aligning interests across diverse stakeholders. The utility lies in creating new BOs, which once complete don't have to be renegotiated at their different points of application, as well as in utilizing established BOs – as these foster compatibility and relevancy between worlds without the need for direct interaction – and the unforeseen negotiations this can bring. Whereas finding or creating objects that different social worlds can utilize independently without the object coming apart or losing relevance in the face of these differing intentions can seem daunting, industrial practitioners create and utilize such objects *every day*. In addition to ready-made standards, consider a *homegrown* specification for validating a critical component from an external supplier. When designing this BO, it is important to consider that to be successful, the results generated by this test specification must simultaneously accommodate the diverse needs of different *worlds*, without their needing to refer back to each other later to interpret them in their own unique contexts. This requires reflection over which social worlds the object intends to serve. In this case, the specification will shape work arrangements within the R&D, Quality and Procurement functions of the host company, the laboratories completing the tests, and the Supplier. The next question would be, who speaks for these social worlds and can reveal the unique or shared intentions and objects of their work arrangements? Finally, the architect(s) of the specification should ask, how will these spokespersons be involved in formulating the specification? Because a BO is per definition an *infrastructure* for managing work arrangements, focusing on the elements supporting such infrastructures provides a novel means for technology managers and engineers to *structure* cooperation across diverse groups with varying intentions and ensure the relevance of their individual actions for a greater whole. The ability to identify an existing object as a BO is also an important part of *staging with objects.* Recognizing which objects are performing, or ultimately could be made, to manage the flows of complex work arrangements across collaborators can assist practitioners in structuring strategies to either accommodate or move away from these objects. Analyzing an existing BO also provides insights into the *minimal* characteristics any new object must possess to replace an existing infrastructure, and perhaps more importantly can sensitize attention towards BOs 'in-the-making'. Such quasi-stable objects may possess potential for managing complex action (like a preliminary business case) but have not achieved sufficient stability within an existing network to withstand interactions outside of this network. A potential drawback of stability is that once a BO has been successfully *integrated* into a network of associations it can be difficult to displace, or even to modify. The next object to be considered neither assumes nor demands stability, making it useful for understanding *actions* occurring outside of such cooperative intersections.

5.2.2. INTERMEDIARY OBJECTS

While boundary objects are *stable* – insofar they must maintain common identities across multiple sites – an 'intermediary object' (IO) can be viewed as an object 'on the move' changing its identity as it oscillates between two different extremes. At the first pole, an IO performs as a 'commissioning object', where it passively and appropriately serves coherent means towards achieving or supporting specific objectives. At the second pole, an IO performs as a 'mediating object', shaping actions and mediations within active and interactive roles. Although BOs and IOs *both* "account for the materiality of things that actors produce and use in a given situation", IOs are understood to *accompany* processes 'in the making' and are mutually shaped in interaction with these processes[25] (see figure 1 for an example). To assist in understanding this complex process, the chief architect behind the IO conceptualization, Dominique Vinck, provides the concept of 'equipping' – which intends to describe how the possibilities and intentions of collective work are reciprocally shaped, *in tack* with properties being conferred on the IO[26]. In order to demonstrate such movement, I combine two of the examples that illustrate 'key tenets of ANT' from the start of this chapter.

To successfully *facilitate* the intentions of its authors, a component specification, must meet multiple requirements simultaneously – the specification's tolerances need to match the capabilities of the factory's manufacturing equipment, be measurable on the factory's quality equipment and be unambiguously interpreted by the users of this diverse equipment. To these ends, a Design Engineer (DE) releases a specification to

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[25] This introduction draws from the book chapter by Vinck et al. (1996), *Objects and Other Intermediaries in the Sociotechnical Process of Product Design: An Exploratory Approach*. The citation is from pages 93-94.

[26] For more on 'equipping' see the article by Vinck (2011), *Taking Intermediary Objects and Equipping Work into Account in The Study of Engineering Practices*.

a Manufacturing Engineer (ME), *commissioning* ME to create a prototype from the specification. To accommodate production processes and manufacture the prototype, the ME then interprets aspects of the specification in ways DE had not foreseen – *equipping* the object with a new unspecified parameter. When the Quality Engineer (QE) is commissioned to measure ME's prototype against the specification, QE, unaware of the new unspecified parameter bestowed upon the prototype by ME, approves the protype as fulfilling the specification. In experiments designed to validate the prototype component as part of a product, a secondary component fails unexpectedly, necessitating that the validation process of the principle component is re-designed in cooperation with an Engineering Expert (EE) in the secondary component's functionality and reliability. As part of this validation process EE asks DE for the magnitude of a parameter EE thinks could be crucial for interactions between the prototype and secondary components, and which EE cannot locate on the prototype specification. DE then ascertains that the unspecified parameter which ME had inadvertently changed and the parameter thought crucial by EE were one and the same. Through *other* processes (which also include specifications, prototypes, measurements and tests) the necessary magnitude of the new parameter is then investigated so that the initial specification can be equipped with this information.

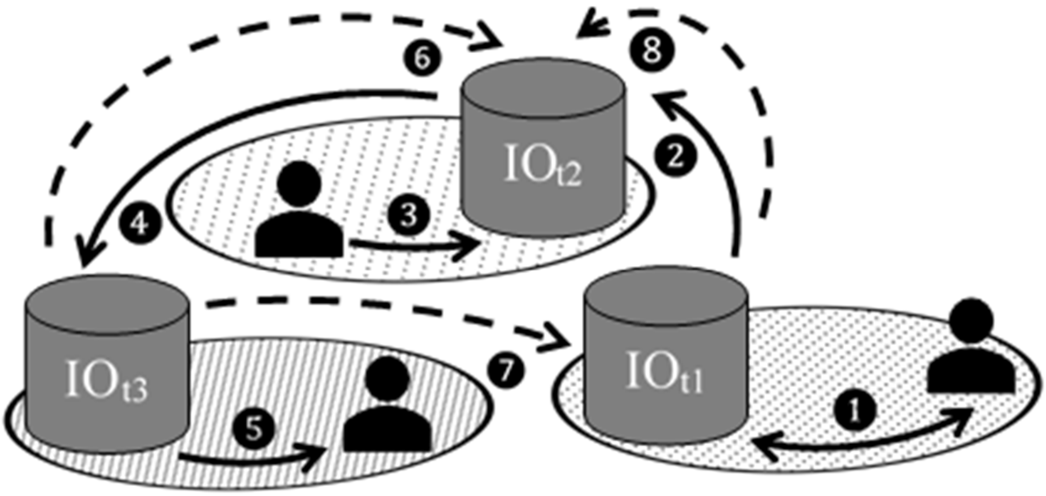

Figure 1: 'Commissioning'' intentions gone awry and the 'mediating' work that follows.

Figure 1 is a simplified and generic illustration of how commissioning intentions can go awry. At ❶ in the bottom left of the figure, an actor creates an IO that is adapted to his work arrangements and intentions – this object is designated t1 for 'timestamp 1'. At ❷ in the figure, the IO's architect deploys the IO as a 'commissioning' object for actors at different sites. Despite these intentions, the actor at timestamp 2 (t2) reinterprets the IO, adapting it to his own working arrangements ❸, before sending it to the actor at t3 ❹. At timestamp (3), the actor will either become aware of the reinterpretation and send the IO back to the actor from timestamp 2 ❻, or remaining unaware of the changes, manipulate the IO per its intended commission ❺ before returning the IO to its architect from timestamp 1 ❼. At this point the architect will either notice the reinterpretation at timestamp 2 and reinitiate the commissioning process ❽ or the work arrangements originating in timestamp 1 will be confounded in interaction with the IO. A combination of both scenarios could also arise.

Variations of this narrative occur regularly in industrial contexts, one could for example replace the 'specification' IO with a 'presumedly known material' from a new supplier or the 'laboratory experiments' with 'end-of-line tests' in running production. What I propose as novel, is that the IO concept provides a means of not only tracing and analyzing the intentions and results of complex networks of associations[27] following (un)successful mobilizations, but provides a means of pursuing a reflective practice, whereby technology managers and engineers can plan for, around and with the objects to which they are exposed or themselves situate – asking themselves when and how objects meant to commission action can betray initial intentions and become mediating, or how supposedly mediating objects, meant to foster multi-sided collaboration, lock specific actors into commissioned roles – both before and while these mobilizations take place. I will return to this subject in Chapter 5.3, but for now it is sufficient to say that a focus on the *equipping* of *intermediary objects* can assist technology managers and engineers in developing strategies by which instable IOs can develop necessary characteristics to accommodate stable *mediating* or *commissioning* roles as *boundary objects* – or not[28].

Whereas boundary objects and intermediary objects have been used extensively to describe and analyze engineering work (initially by their architects – see Chapter 2.3), the next concepts to be considered, *(re)writing devices* and *calculative devices,* were designed for other ends: The calculations of economic agents. For reasons I hope to make apparent, I propose that these concepts, while designed to address processes of *economic* network-stabilization are equally useful for addressing processes of *technologic* network-stabilization.[29]

[27] That objects provide access to these traces and intentions is elaborated by Vinck (2012) in the book chapter, *Accessing material culture by following intermediary objects* – albeit in a more research-focused context.

[28] For more specific examples of how BO and IO conceptualizations can support industrial practice, see three of the papers supporting the development of this framework: *Staging with Objects: Translation from Technology to Product Development* (Bates 2020, forthcoming); *Positioning Patents to Perform Coordinative Action in Industrial Technology Development* (Bates 2020); and *Staging Referential Alignment in Industrial-Academic Collaboration* (Bates and Juhl 2020, forthcoming),.

[29] Although it is uncertain that the architects of *(re)writing devices* and *calculative devices* would agree with this statement, it is discussed in depth in a publication by Bates and Clausen (2020) supporting this dissertation: *Engineering Readiness: How the TRL Figure of Merit Coordinates Technology Development*.

5.2.3. WRITING AND REWRITING DEVICES

Callon[30] describes 'writing and rewriting devices' – *(re)writing devices* hereafter – as texts through which systems of collective action are established and transformed in a process of 'successive adjustment', which allows agents to formulate demands, and the actions required to respond to these demands, as they are being progressively manifested. In this manner, (re)writing devices make complex systems of action manageable and controllable, in real-time, without necessarily reducing or limiting the complexity of these systems. Such texts are built up, disseminated, utilized and amended collectively but are managed and stored centrally. This enables *centralized* actors to manage and correlate the effects of different sequences of *distributed* action as observed and measured results. An example from industry is a new test specification created by an engineer and sent to the test laboratory. When the laboratory technician or test engineer contacts the author of the specification for additional details that are necessary for selecting/constructing the ideal test panel (like the sampling rate of measurements or viscosity of the hydraulic fluid) these details will be written into the document according to the engineer's intentions with the test. This interaction also flags these details as necessary parameters that should be included in future specifications for similar test-setups. Finally, these previously unconsidered parameters are now included as *results* which engineers can utilize in future analyses (or not) as part and parcel of existing working arrangements. (Re)writing devices thereby perform to reduce tensions "between complexification and simplification, between decentralized initiatives and centralized control". As such, (re)writing devices do not only *describe* an existing reality – they also perform to *format* reality as they simultaneously enable and strengthen associations between collective and individual action.

(Re)writing devices may exist physically or virtually. For the purposes of this framework, (re)writing devices can include reports, presentations, templates, process models, figures of merits or certain types of specifications. To demonstrate how (re)writing devices can establish and transform collective systems of action, I return to the example from the previous subsection, where experiments designed to validate a prototype component as part of a product were necessarily re-designed to accommodate unexpected interactions with a secondary component. For this process to be successful, re-designed experiments must maintain their associations with the initial experiments from which they were engendered – while maximizing the amount of existing information that can be retained and made relevant across the different (and only limitedly foreseeable) contexts of the new experiments. In the industrial

[30] Unless otherwise noted, this subsection takes root in the book chapter by Callon (2002), *Writing and (Re)Writing Devices as Tools for Managing Complexity.* The citation is from page 212.

firm considered here, 'engineering-reports' are a type of (re)writing device that perform to structure, guide and improve this process.

An engineering-report can be understood as a repository housing all relevant information for specific development projects. This repository is structured according to a template for a 'finalized report', which not only *documents* the 'Purpose', 'Background', 'Procedures', 'Analyses', 'Conclusion' and 'Date-of-completion' for a development project, but also *defines* the sequences of action by which a diversity of named agents (e.g. customers, suppliers, laboratory and measurement technicians, mechanical engineers, metallurgists or tribologists) complete these actions and record their *individual* observations and results in a *collective* document. Whereas finalized engineering-reports generate 'consensus' and are generally accepted as evidence upon which future analyses and conclusions can be constructed and confirmed, unfinalized engineering-reports are broadly recognized as a repository of information 'still being negotiated', where alliances, oppositions and the agent-cum-authors brought into support them continue to change.

Returning to Callon, (re)writing devices are both *results of*, and *starting points for*, associating heterogeneous requirements and making them compatible. As such, (re)writing devices contribute to multiple ends in processes of technology development:

- They identify the requirements necessary for a system of collective action
- They document observations and results in a format that enables unique and unrelated, historic and future decision-making associable and comparable
- They codify different work arrangements, allowing agents to execute novel or specific endeavors from within recognizable or generalizable contexts
- They centralize distributed action, its effects and interpretations into a single document where diverse agents can write, erase and amend, collectively and individually – occasionally in real-time

Technology managers and engineers create and utilize a variety of (re)writing devices. By reflecting over these four contributions, industrial practitioners can ask themselves which (if not all) of these aspects are important for their specific intentions and contexts. Practitioners can then focus on the most relevant of these aspects in how they are utilizing an existing object or consider how to prioritize or achieve these aspects in their design of a new object. That (re)writing devices *describe* existing realities while they simultaneously *format* realities make them extremely potent. Decision-making tools like NPD-process models and the TRL figure of merit are excellent examples of complex (re)writing devices that depend on a number of textual results. While it is generally understood that these textual results are subordinate to (*paced* or *defined by*) the overarching NPD or TRL devices, it is important to consider that these underlying results are manifestations of the *progress* that NPD *milestones* or TRL *levels* are designed to measure. Understanding how these manifestations –

which are also (re)writing devices – are associated and stabilized can have enormous effects on NPD and TRL measurements and the decision which they generate.

(Re)writing devices are an example of 'centres of calculation' – the literal or metaphorical sites which allow spokespersons of all sorts, from sea captains to laboratory managers, to hold a variety of elements in circulation while still being able to manage them[31] – as does the next and final object to be considered here.

5.2.4. CALCULATIVE DEVICES

'(Re)writing devices' and 'calculative devices' are closely related. Both conceptualizations take outset in 'centers of calculation' and aim to support cycles of accumulation through which points become centers "by acting at a distance on many other points"[32]. Both objects enable agents to control and manage complex systems of action, *without* the necessity to reduce or limit the complexity of the actual systems.

Still, there are important differences which make them useful for *staging with objects* in differing contexts. In their simplest sense, (re)writing devices are texts which reciprocally document and shape observations and results within collective systems of action. Calculative devices, on the other hand, are solely purposed with the collective production and dissemination of *results*: New and stable entities, which have been prefigured through a variety of considerations, in order that these entities can leave the calculative space and carry its intentions without bringing the elements shaping these intentions with it. The architects of the 'calculative device' conceptualization, Callon and Muniesa, have defined this calculative process as encompassing three *phases* or 'moments': the circumscription of agencies, the organization of encounters and the establishment of conventions. Before describing these phases, it is worth noting that Callon and Munesia do not consider 'calculation' in any traditional sense (i.e. as limited to numerals, arithmetic or mathematical operators). Rather, their definition blurs *a priori* distinctions between *calculation* and *judgement*: "Calculation starts by establishing distinctions between things or states of the world, and by imagining and estimating courses of action associated with those things or with those states as well as their consequences".[33]

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[31] For more information on 'centers of calculation' see the book by Latour (1987), *Science in Action: How to Follow Scientists and Engineers Through Society*,

[32] See page 222 in the same book by Latour.

[33] Unless otherwise noted, this subsection is rooted in my practical interpretation of the article in which Callon and Muniesa (2005) first defined the concept: *Peripheral Vision: Economic Markets as Calculative Collective Devices*. The citation is from page 1231.

The first moment of a calculative device, *the circumscription of agencies*, is where the entities that are to be taken into account are identified, moved, ordered and arranged, literally or through delegation, according to the demands of the calculative 'space' in which the calculation will take place. Such spaces have varying degrees of complexity, from the simple, like a cash register, invoice or spreadsheet, to the complex, like a laboratory, factory or company. The second moment*, the organization of encounters*, is where the finite number of entities that were circumscribed in the first moment are associated and made relevant for one another through manipulations and transformations. Here again, the complexity of this operation can vary – from scanning the barcode on a block of cheese to ascertain its price, to employing electrolysis to decompose a metallic compound and determine its base elements. In the third moment, *establishment of conventions* enables an accomplished calculation where a new entity is produced and extracted as a result. This result can be the addition or subtraction of a sequence of numbers, a comparison, a structured list, a binary choice or an assessment, but it must precisely correspond to the manipulations and transformations that were conducted within the calculative space and link the finite number of entities that were taken into account – Callon and Munesia call this to 'summa-rize'. The strength of such results is that they can ultimately be situated to perform in contexts outside of the calculative space, without the entire apparatus upon which the results rest needing to accompany them. The three moments of a calculative device are illustrated in the following example.

In order to limit the number of experimental tests required to select and validate the optimal design of a hydraulic component, a computer-aided engineering (CAE) specialist is tasked with developing a parametric model to determine the number of cycles that different versions of the design are expected to survive in various applications. Drawing on the first moment of a calculative device, the calculative space is initially defined as the commercial software in which the model will be developed. In addition to the CAE Specialist, the minimum input parameters (or entities) required by the software include 3D computer-aided design (CAD) models of the different component designs, mechanical properties of the material of which the component is comprised and the characteristics of the different applications in which it is employed. Because these entities exist (and will be manipulated independently) outside of the software that initially defined the space, the calculative space must now be re-defined to encompasses and include additional entities:

- The Design Engineer responsible for specifying and developing the different 3D CAD model designs in the R&D Department.

- The Purchasing Specialist in the Procurement Department who is responsible for the raw material that is defined by industry standards.

- The Manufacturing Engineer in the Operations Department who is responsible for the fabrication processes that alter the component's mechanical properties from those of the raw material.

- The Product Application Engineer in the Sales Department who is responsible for contact with the original equipment manufacturers that can define characteristics of the different applications.

Now that the calculative space has been expanded to include the additional entities necessary for the CAE Specialist to develop a parametric model for determining (*calculating*) the number of cycles different designs are likely to survive in various applications, **the second moment**, *the organization of encounters,* can enter into force. Here, the individual networks defined in each of the bullet points must be associated and made relevant for one another so they might be situated in the parametric model by the CAE Specialist in ways that could very well foster new entities and re-alter the nature of the calculative space (e.g. need for a *Metallurgist* able to decompose the raw material into its *base elements* using *electrolysis* at the *Company Laboratory* to verify compliance between industrial standards and the raw material). The ways by which these associated entities are ultimately 'situated' by the CAE Specialist are the subject of **the third moment**: *the establishment of conventions* for calculation so that the number of cycles different designs are likely to survive in various applications can be manifested, compared and finally circulated outside of the calculative space. In this case, these conventions will be defined in interaction with the commercial software that initially defined the space and take root in finite element methods of analyses.

Like the other objects already considered, the concept of calculative devices sensitizes to the fact that *results, actions* and *agency* do not spring from nowhere but are themselves products of *association,* and when viewed as 'composite entities' – shaping and shaped by a variety of sociotechnical elements – can foster useful reflections about how such entities *are, were* or *can be* manipulated and situated to a diversity of ends. My introductions to these objects are neither exhaustive nor final. Rather, they are intended to provide a starting point from which such reflections can support 'on-the-fly' decisions associated with the means by which *objects* foster, serve or eventually become *objectives*. With general introductions to four objects now in place, the following subsection focuses on putting these reflections into practice.

5.3. *STAGING WITH OBJECTS* AS INDUSTRIAL PRACTICE

In a forthcoming book chapter[34], I conceptualize *staging* "as a practice by which entities, defined as networks composed of humans and non-humans as well as material and immaterial objects, are materialized and (re)assembled to perform in processes of translation". A guiding principle of this practice is that the agency to situate and define objects is viewed as a complex process of negotiation that does not reside in a single actor. Rather, objects are seen as reciprocally (de)stabilized by the effects of actors' changing positions as they navigate changing situations. This subsection is concerned with how *staging with objects* supports three key dimensions of transitioning technologies from invention to commercialization:

1. Facilitating engagement across specialized networks
2. Fostering common points of reference and alignment of interests across diverse stakeholders, and
3. Helping actors to articulate and mobilize resources within their organizations

Although each of the key dimensions are considered individually, the subsections are similarly structured. They begin by introducing the practical relevance of the dimension. A simplified example from an industrial case is then provided. Finally, information organized according to a series of questions, that can be useful for understanding and ultimately *staging objects* associated with the specific dimension, is presented in different formats for each of the dimensions. These descriptions, figures and tables stem from personal attempts to organize and visualize my own cognitive efforts and shift focus from the many *objectives* vying for attention in technology development projects, to the *objects* and *associations* of which these objectives are comprised. These efforts have certainly assisted me in making sense of and responding to the demands of my own practice in real time by allowing me to prepare for, if not always accurately predict, or respond to altered or new associations. Table 1 presents some simple questions that technology managers and engineers can ask themselves when faced with decisions related to their objectives. These types of reflections are important because even *seemingly* modest decisions or actions can have significant consequences for development projects. I have often had to place a specific objective on hold, or sometimes change it completely, because a different element of the technology than the one being targeted interfered with the results, or revealed itself to be of more critical concern. Even trivial *actions* can inadvertently flood the development space with new objects and knowledge that paralyze, limit or change possible means of action. Therefore, a principle focus of 'staging with objects' is to retain *as many* elements as possible while *still being able* to manage them. This requires conscientious attention to the possible consequences of bringing (or

[34] See the book chapter by Bates (2020, forthcoming), *Staging with Objects: Translation from Technology to Product Development.*

receiving) new or altered objects into the development space. The general questions in table 1 are grouped according to topics I have found useful in stimulating reflection around objects and how they can accommodate or support specific objectives. Practitioners are encouraged to expand or amend these topics and questions as they see fit. It is certainly likely that other skilled practitioners can provide more meaningful, intuitive or understandable ways of organizing and visualizing information gleaned from their own variations of table 1 and are encouraged to do so.

The questions of table 1 intend to stimulate reflection around the realms of possibility for *staging objects* towards specific objectives. Understanding relationships between an object, these topics and overall objectives of the technology development space are important because *means of action* within a development space will utterly depend upon the reading and navigation of the situation in which a practitioner finds themselves and the (assumed) potential the objects at hand. The presence of any one of the conceptualizations of objects presented in Chapter 5.2 can also indicate key strategic concerns to help practitioners navigate diverse situations: *Boundary objects* rest at intersections of cooperation; *Intermediary objects* are 'objects on the move' oscillating between commisioning and mediating roles; *(Re)writing devices* and *calculative devices* provide different means of 'managing at a distance'. These sensitizing concepts of objects (as well as the glossary of Chapter 5.4) can thus provide guidance in identifying, defining, manifesting and maintaining dynamic associations across, between and within complex networks of heterogeneous elements – as well as the position and possibilities for action of the technology managers and engineers using them.

Table 1: Topics and questions for understanding and ultimately staging objects towards achieving specific objectives

Topic	Question(s)
Identification	Which objects are necessary to fulfill, demarcate or expand an objective?
Localization	Will these objects travel between networks or rest at the intersections of multiple networks? Do associated networks have equal say in how these objects are situated and manipulated?
Intent	What do the objects intend to perform or accomplish? How will these objects facilitate action or be facilitated by action?
Spokesperson(s)	Who speaks for how the objects are manipulated, situated or interpreted? When or how do spokespersons change?
Composite Elements	Of what sociotechnical elements is the object composed? Is it possible to manipulate these components individually and exclusively or must they be addressed simultaneously?
Stability	How is the stability of the object achieved or defined? Can the object be replaced or changed without destabilizing the network it supports?

5.3.1. FACILITATING ENGAGEMENT ACROSS SPECIALIZED NETWORKS

Let me begin by defining ‘engagement’ as an actor being occupied with some type of action for any duration of time with varying levels of commitment. Engagement can be transitory or enduring, depending on the intentions, possibilities or limitations of the involved parties – where isolated or collective commitments to the encounter also vary according to the same parameters. Because objects both constitute and trace marks of their authors and relations, they bear specific information about the intentions and conditions influencing their migration between specialized networks and how engagement *is*, *was* or *could be* fostered across or within these networks.

In processes of technology development, an *object* is usually (if not exclusively) supporting or performing as the principle *objective* facilitating encounters between specialized networks. An invention may evolve from an immature conceptualization loosely associated with abstract ideas of functionality or reliability, but it gains tangibility through interactions with a myriad of *other* objects – including money, patents, software, specifications, prototypes, process models, and manufacturing and test equipment – spread across a diversity of networks "designed, trained, or fitted for one particular purpose or occupation"[35]. Not only do objects provide a direct means for identifying and analyzing the common structural elements holding such networks together, more often than not, objects *are* these structural elements – expanding or impeding possible means of action. Acknowledging that objects foster, support and limit engagement from, within and across specialized networks, provides a robust means for integrating or strengthening necessary or desirable associations between these networks. Consider the following example.

Researchers at a university specializing in friction and lubrication (*tribology*) recently established a start-up company focused on developing and manufacturing a new water-miscible replacement for the *de facto* standard hydraulic lubricant dominating the industry. The researchers leverage a long-term association with a leading manufacturer of hydraulic products to request support in defining and executing practical experiments to prove, and ultimately optimize, the functionality and reliability of the new lubricant for the market in which they hope to compete – framing the cooperation as an exercise in 'sustainability', which they know to be a key aspect of the manufacturer's brand. To this end the collaborators must define, develop and maintain a test-setup servicing the tangential goals of the three organizations.[36]

[35] Merriam-Webster. (n.d.). Specialized. In Merriam-Webster.com dictionary. Retrieved June 8, 2020, from https://www.merriam-webster.com/dictionary/specialized.

[36] This is a simplified description of a case considered in two publications supporting development of this framework. A book chapter by Bates and Juhl (2020, forthcoming), *Staging Referential Alignment in Industrial-academic Collaboration;* and a working paper by Juhl and Bates (2020), *Referential Alignment: Situating Knowledges and Materialities in Innovation Science*.

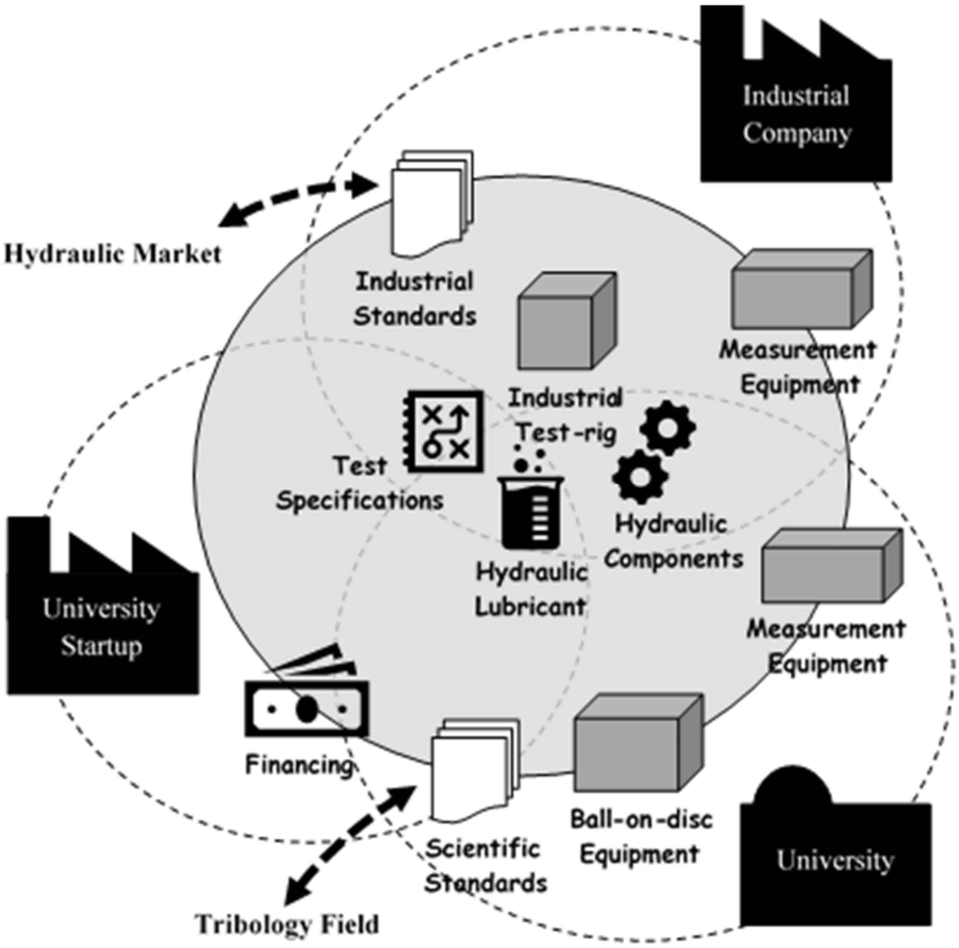

Figure 2: Objects facilitating engagement across specialized networks, situated according to their affiliations across three collaborating organizations.

Figure 2 intends to visualize principle objects from which the test-setup is configured and translated, according to their affiliations across specialized networks. The shaded circle at the center of the figure represents the development space shared by the three collaborators – defined as the test-setup through which the new lubricant can be made relevant for the hydraulic market. Principle objects supporting the collaboration are positioned according to where they are negotiated. Objects lying completely within the borders of the development space are wholly available for the collaborators' disposition. Objects lying at the borders must be negotiated with spokespersons for other networks outside of the development space. Two of the objects, *Industrial* and *Academic Standards*, are 'boundary objects' – stipulating or enabling criteria for maintaining associations within the larger networks of which the collaborators are a part – and fall outside of the collaborators' direct control. Here, it is important to note that BOs are important to recognize *because* they structure (and ultimately) limit the ways in which novel technologies can be made relevant for different networks. Moreover, these BO's importance as standards made them impossible to replace or avoid. To accommodate these challenges, the collaborating partners placed *other* objects between their objectives and the standards. Instead of utilizing an industrial standard to define properties *of* the novel lubricant (which were inequivalent to the dominant lubricant which the standard supports), they utilized the industrial standard to define these properties as *output parameters of* their test-setup. This was not a linguistic exercise. Because the industrial test-rig was designed for validating hydraulic component designs using the dominant lubricant (and not differences between lubricants) it provided no information about these standardized properties. It was therefore necessary to bring another (ball-on-disc) 'test-rig' into the space with its associated objects. While this added complexity, reconstituting the development space and exponentially increasing the number of associations therein, this *staging* made it possible to compare the precise effects of different lubricant properties (than those of the dominant lubricant *according* to the industrial standard) on the functionality and reliability of hydraulic components. The collaborators could thus relegate the industrial standard to a background role (albeit as a key principle component) within a new BO: 'the test-setup'.

Analytically, figure 2 provides a means of identifying and separating principle objects according to the actors that must be engaged in order to develop and maintain these objects within the collaboration. Figure 2 was initially meant as visualization to help me make sense of my my PhD research. It began to take form at the beginning of the project as a simple sketch. I updated the initial sketch after important events with the collaborators, adding and removing objects as they (dis)appeared. I found that understanding the affiliations of principle objects upon which the test-setup depended – for example the standards over which collaborators have limited control, or necessary equipment that must be negotiated outside of the development space with other specialized networks – was a necessary step towards developing strategies for fostering engagement by, for and around these principle objects. Figure 2 provides a helicopter view of the specialized networks involved in the collaboration, the *Industrial Company*, the *University* and the *University Startup,* as well as the larger *Hydraulic Market* and *Tribology Field* of which they are a part, but the same logic can be applied to gain a frog's-eye view of a specialized network or even individual elements of which it is comprised.

5.3.2. FOSTERING COMMON POINTS OF REFERENCE AND ALIGNMENT OF INTERESTS ACROSS DIVERSE STAKEHOLDERS

Once engagement across specialized networks is achieved (however provisionally), it must be maintained or adapted, usually in association with parameters that are only partially defined or considered. Common points of reference and alignment of interests play an important role in this endeavor, enabling stakeholders to define and prioritize complex infrastructures of objects and work arrangements. Without them, concepts of *what* is relevant and *how* this relevance can be maintained (what Latour calls 'matters of concern'[37]) become difficult, if not impossible. But, perhaps more importantly, common points of reference and aligned interests are concurrently fostered, contested and sustained *through and with* the objects and work arrangements they are intended to support, and into which they are ultimately integrated. Consider the following example.

The Vice-president of a Business Unit invites a Technology Development (TDP) Team and Sales Team to a kick-off meeting with the Product Development (PDP) Team who will be responsible for implementing the new technology into a product. The topic of the meeting is to create a 'plan of action' for achieving the first 'milestone' of a New Product Development (NPD) process model dimensioned á la Cooper (see Chapter 1.2.1). According to the company sanctioned process model, 'Milestone 1' must include a 'Business Case' as well as a 'Technology Readiness Level (TRL) Assessment' of the new technology according to the demands of the Business Case. The stakeholders agree to leverage their last TRL Assessment to solidify a preliminary Business Case in cooperation with customers. This deceivingly simple endeavor quickly evolves into a larger scale investigation around the purpose of the technology and the markets for which it is deemed suitable.[38]

Table 2 organizes information garnered from the topics and questions presented at the start of Chapter 5.3. Considering the 'Business Case and 'TRL Assessment' that define 'Milestone 1' in the 'NPD Process Model', as conglomerate entities (possessing attributes not shared by their individual components), and dividing them into their primary (and known) composite elements reveals a multitude of objects reciprocally shaping one another. Moreover, table 2 reveals *where* these objects and their underlying networks may be manipulated, situated and made-sense-of *individually* or *collectively,* and enables reflections around *where* or *how* complexities pertaining to 'referential alignment' – "the quality of referential relationships that enables knowledge artefacts and processes to refer back and forth between different material, organizational, local and temporal settings"[39] – are most critical or vulnerable.

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[37] In the book, *Reassembling the Social: An Introduction to Actor-network-theory,* Latour (2005 – see page 114) proposes and formulates 'matters of concern', which he explains as uncertain, disputed, objective, atypical, "and above all, interesting agencies" more readily understood as 'gatherings' than 'objects'.

[38] This is a simplified description from a case supporting this framework's development. See Bates (2020, forthcoming), *Staging with objects: Translation from Technology to Product Development*.

[39] See page 196 of Bates and Juhl (2020, forthcoming), *Referential Alignment: Situating Knowledges and Materialities in Innovation Science*.

Put simply, table 2 provides an overview of the *objects* (including their composite elements, location, spokespersons and stability), that define the *objective* to which the stakeholders are tasked. One could also see it as an overview of the *structural elements* supporting the *infrastructure* of objects and work arrangements that defines the development space. In this exercise, considerations necessary to produce the table (which could certainly take alternative forms) are meant to nurture insights into the key *associations* defining an objective – in this case the task of leveraging results from a successful TRL Assessment to solidify a preliminary Business Case. Moreover, the information arranged in the table can help indicate interactions *where* common points of reference and alignment of interests across these associations are likely to emerge. In my experience the act of creating such a table nourishes reflections around *how* interests or references may diverge or converge at specific junctures.

Table 2: Objects reciprocally shaping common points of reference and alignments of interest in an industrial case-study

Identified Objects	Localization	Intentions	Spokespersons (by status)	Composite Elements	Stability
NPD Process Model (Milestone 1)	Centralized templates and guidelines for coordinating distributed activities across functions	Coordinate diverse development activities according to a series of sequential milestones	• Top Management • PDP Manager	• Business Case • TRL Assessment	Coordinates development according to an assumedly stable, mechanistic and realizable process
Business Case	Centralized documents defining distributed development activities across functions	Define products, market demands profitability and volumes	• Top Management • PDP Manager • Sales Manager	• Product Specification • Concepts of Functionality & Reliability • Market Feedback	Collectively defined. Assumedly stable and realizable at Milestone 1
TRL Assessment	Centralized documents tying efficacy to distributed development activities across functions	Prove efficacy of technology per Business Case requirements	• TDP Manager • PDP Manager • Sales Manager	• Concepts of Functionality & Reliability • Patents • Test Specifications • Prototypes • Test Equipment • Methods of Analysis	Collective evaluations according to an assumedly stable and mechanistic process
Product Specification	Centralized templates and guidelines for defining market specification	'Charter' defining the product's technical requirements	• Sales Manager • PDP Manager • TDP Manager	• Business Case • Concepts of Functionality & Reliability • Market Feedback	Collectively defined. Assumedly stable and realizable at Milestone 1
Concepts of Functionality & Reliability	Defines, guides and measures TDP progress according to PDP and Sales Team feedback	Support development of the technology per Business Case requirements	• TDP Manager • PDP Manager • Sales Manager	• Business Case • Product Specification • Patents • Prototypes • TRL Assessment	Flexible process. Iterative activities aimed at 'black-boxing' the technology
Patents	Must define and protect feasible functional principles within a global market	Appropriate technology for commercial use	• TDP Manager • Sales Manager	• Product Specification • Concepts of Functionality & Reliability • Business Case	Become stable at time of application
Test Specifications	Must reflect customer applications and be utilizable in both TDP and PDP	Develop and prove the technology for a global market	• TDP Manager • PDP Manager • Sales Manager	• Product Specification • Concepts of Functionality & Reliability • Patents • Prototypes • Market Feedback • Methods of Analysis	Flexible templates for defining repeatable and reliable experiments. Assumes known and stable market demands and working principles
Prototypes	One-piece-production in TDP that can scale to industrial manufacturing in PDP	Develop and prove the technology for a global market	• TDP Manager • PDP Manager	• Product Specification • Concepts of Functionality & Reliability • Patents	Flexible process. Iterative activities aimed at 'black-boxing' the technology
Test Equipment	Must be utilizable in TDP and PDP and communicable and relevant in multiple contexts	Develop and prove the technology for a global market	• TDP Manager • PDP Manager	• Test Specifications • Methods of Analysis	Assumedly stable test-setups aimed at 'black-boxing' the technology
Methods of Analysis	Must be utilizable in TDP and PDP and communicable and relevant in multiple contexts	Develop and prove the technology for a global market	• TDP Manager • PDP Manager • Sales Manager	• Test Specifications • Test Equipment	Developed collectively in a dynamic and iterative process aimed at 'black-boxing' the technology

5.3.3. HELPING ACTORS TO ARTICULATE AND MOBILIZE RESOURCES WITHIN THEIR ORGANIZATIONS

In technology development, the mobilization of resources is closely tied to the ways by which knowledge is configured, stabilized and facilitated across a variety of actors and objects through organized encounters spanning diverse stakeholders. *Mobilization* was defined earlier as the *actualization of mandates* (however temporary) which have been established through a process of *problematization*, *interessement* and *enrolment* (see Chapter 5.1). For the purposes of this framework, the three moments by which mandates are *established* can be summarized as a process of *articulation* – "the action or manner of jointing or interrelating, [or] the state of being jointed or interrelated".[40] Put simply, a *mandate* can be viewed as a stable network of heterogeneous elements assembled to support a specific objective. Ideally, such *articulated* mandates will include the gamut of organized encounters of which a *mobilization* is comprised. Still, in processes of technology development, these encounters are not always known, often ill-defined and can unfold expectedly – rendering *presupposed* objectives difficult or impossible to achieve within the confines of the resources that have been allocated. Mandates may be finite, but the ways by which articulations of resources can serve to impede or achieve the objectives they are formulated to support are inherently more difficult to delineate.

That the *articulation* and *mobilization* of resources are closely intertwined is a familiar concept for technology managers and engineers. Industry employs a variety of well-structured objects for constructing and approving such articulations in ways that assumedly support and define their later mobilization. These include Application for Expenditure (AFE) or Return on Investment (ROI) templates, as well as less-structured agreements for how resources will be allocated or shared at decided intervals, according to premeditated interactions (like the NPD process model or TRL Assessments mentioned earlier). Because, these industrially sanctioned objects for approving resource allocations are *explicitly* designed to limit resources consumed in a development process, technology managers and engineer are often adept in linking specific resource allocations with other development projects or more general business strategies outside of their *direct* mandates. Drawing on this familiarity, I propose that a focus on how *associations* between objects and actors are *(de)stabilized* in mutually shaping processes of *articulation* and *mobilization* can support *both* aspects of resource-oriented objectives in ways that make complex systems of action more manageable without necessarily reducing the complexity of these systems. Consider the following example.

A Technology Development (TDP) Team requires an unexpected infusion of resources to accommodate timelines and deliverables specified by the company

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[40] Merriam-Webster. (n.d.). Articulation. In Merriam-Webster.com dictionary. Retrieved July 30, 2020, from https://www.merriam-webster.com/dictionary/articulation.

sanctioned NDP process model – which requires higher TRL ratings than the team has yet obtained before the project can successfully transition to a Product Development Project (PDP). To achieve the higher rating, ambiguous performance results between prototypes tested in laboratory experiments and vehicle tests at the company test-track must be understood and addressed. To accomplish this, the TDP Team requires additional technical specialists, hailing from two different departments in the firm, as well as significant laboratory investments.[41]

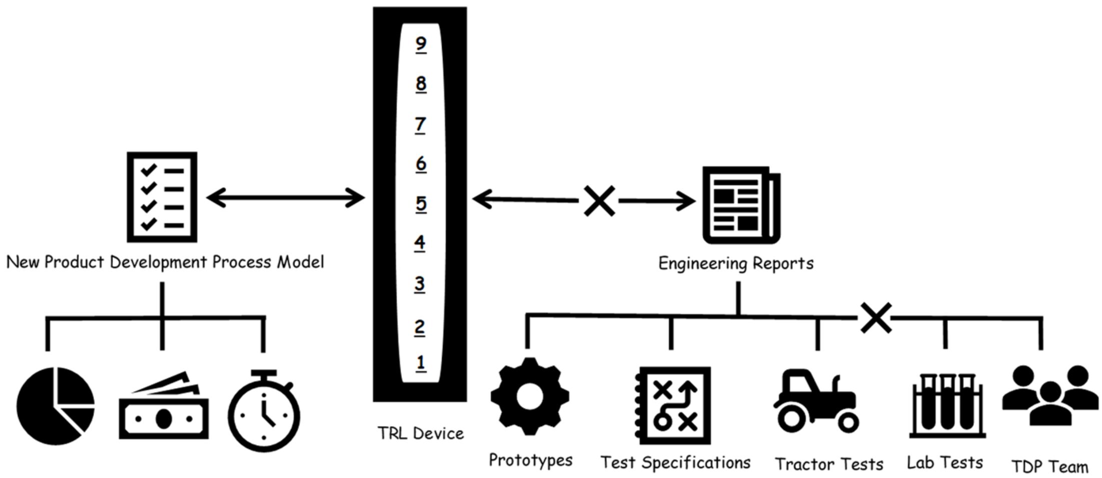

Figure 3: Organized encounters as they are structured in interaction with the Technology Readiness Level management tool.

Figure 3 illustrates associations between the principle actors and objects that are affected by the current situation as these are organized in interaction with the TRL device. To the left is the NPD process model pacing development of the new technology through specific demands to performance and profitability at a particular milestone. At the center of the figure is the TRL device by which the efficacy of different aspects of the technology are measured according to guidelines established through interaction with the NPD model. On the right are the 'Engineering Reports' documenting this efficacy, according to *matters of concern* engendered through and for TRL Assessments. An X indicates that presumed associations between these reports and TRL are not intact. Below the reports are their composite elements, where an X once again indicates a break in necessary associations between the *prototypes*, *test specifications* and *tractor tests* on the left and the *laboratory experiments* and *TDP Team* on the right.

Like figure 2, figure 3 provides a helicopter perspective of associations between heterogeneous elements and could be advantageously repeated at the frog's-eye view

[41] This is a simplified description from a case supporting the development of this framework. See Bates and Clausen (2020), *Engineering Readiness: How the TRL Figure of Merit Coordinates Technology Development.*

at the points where associations are fractured – to identify relations between the 'next-level' of composite elements and eventual disconnects between objects and actors. Once again, shifting focus from *objectives* to how the *objects* and *actors* defining or supporting these objectives can be manipulated and situated, or as in this case expanded, reveals details that might perform to de- or re-stabilize the networks of which one is a part or responsible. In this example, achieving "sufficient technology readiness" became an 'obligatory passage point' (OPP). through which all other development activities transpired and were defined. Resource infusions into the laboratory and TDP Team could thus be articulated and mobilized as possible *means* of reconciling fractured, albeit *necessary*, associations between engineering work arrangements (as these are defined and demonstrated in engineering reports), the TRL device and NPD process model guiding the development process. Technology development projects include numerous OPPs. As this example demonstrates, connecting objects to these OPPs can be a successful strategy for moving development forward. On the downside it can be very difficult to separate an object from an OPP once the association has been accepted, without destabilizing the OPP itself. It is therefore important that the underlying elements which comprise an OPP-supporting-object have not only been identified but can also be manipulated or re-arranged to accommodate unintentional effects on the OPP as a consequence of *staging* with the OPP-supporting-object. An example of this would be associating a customer questionnaire with a Business Case, which is often an OPP for moving a project from invention to commercialization. Once accepted as necessary for the Business Case it will be very difficult to disassociate the questionnaire's findings from the Business Case – which could delay the transition from invention to commercialization that the OPP was defined to support.

5.4. GLOSSARY OF SENSITIZING CONCEPTS FROM SCIENCE AND TECHNOLOGY STUDIES

Table 3 provides an overview of the sensitizing concepts and definitions utilized in this methodological framework. This glossary is heavily inspired by a glossary of 'social shaping concepts' compiled by Russel and Williams[42], who stress, "that the significance of a novel concept is unlikely to be apparent in the definition alone, but rather in the use and effect of the term". Practitioners may find that a concept might aptly describe the performance of an object in one context and less aptly describe the same object in a different context. Moreover, it may be necessary to draw on multiple concepts to describe various characteristics of the same object.

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[42] See the chapter *Social Shaping of Technology: Frameworks, Findings and Implications for Policy with Glossary of Social Shaping Concepts*,by Russel and Williams. The citation is from page 108.

Table 3: Glossary of sensitizing concepts from Science and Technology Studies

Sensitizing concept	**Definition**	**Exponents (considered here)**
Boundary Objects	Such objects involve a many-to-many process of interessement, allowing collaborating entrepreneurs to reduce local uncertainty while maintaining coordinated cooperation between allies through any number of coherent sets of translations.	Star and Griesemer 1989: 390-391 Star 2010
Calculative Devices	The three moments of a calculative device are defined as follows: "a) circumscribe the group of calculative agencies that are to be met, by making them identifiable and enumerable; b) organize their encounter, that is, their connection; and c) establish the rules or conventions that set the order in which these connections must be treated and taken into account (formats, queues, etc.)".	Callon and Muniesa 2005: 1242
Centres of Calculation	"The construction of the centres requires elements to be brought in from far away – to allow centres to dominate at a distance – without bringing them in for good – to avoid centres being flooded". Put simply 'centres of calculation' allow "familiar[ity] with things, people and events, which are distant".	Latour 1987: 243, 220

Sensitizing concept	Definition	Exponents (considered here)
(Devices of) Interessement	The 2nd moment of translation: Interessement of actors requires "devices which can be placed between them and all other entities who want to define their identities otherwise". Devices of interessement are thus integral to "actions by which an entity […] attempts to impose and stabilize the identity of the other actors it defines through its problematization. Different devices are used to implement these actions".	Callon 1984: 208
Enrolment	The 3rd moment of translation: "Enrolment does not imply, nor does it exclude, pre-established roles. It designates the device by which a set of interrelated roles is defined and attributed to actors who accept them. Interessement achieves enrolment if it is successful".	Callon 1984: 211
Heterogeneity/ Heterogeneous Engineering	"[T]he stability and form of artifacts should be seen as a function of the interaction of heterogeneous elements as these are shaped and assimilated into a network" Heterogeneous Engineering "may be treated as a way of thinking about oscillation, absence/presence, uncertainty, and the necessary Otherness that comes with the project of centering"	Law 1986 Law 1987: 113 Law 2002: 136-137 Law 2009

Sensitizing concept	**Definition**	**Exponents (considered here)**
Intermediary Objects	Intended to help identify "actors and characterise the[ir] forms of organisation and coordination, and the agreements binding them in processes of translation". Analytically flexible, the concept denotes objects oscillating between translating goals into results, as commissioning objects, and instigating action and mediation, as mediating objects.	Vinck et al. 1996 Vinck 2011 Vinck 2012: 91
Matters of Concern	[A]ll matters of fact require, in order to exist, a bewildering variety of matters of concern" (Latour 2004: 247). A matter of concern is "[t]he thing itself that has been allowed to be deployed as multiple, and thus allowed to be grasped through different viewpoints, before being possibly unified in some later stage [as a matter of fact] depending on the abilities of the collective to unify them" (Latour 2005: 116).	Latour 2004: 247 Latour 2005: 116 Latour 2008
Mobilization	The 4th moment of translation: ["A] set of methods used […] to ensure that supposed spokesmen for various relevant collectivities [are] properly able to represent those collectivities and not betrayed by the latter".	Callon 1984: 196

Sensitizing concept	**Definition**	**Exponents (considered here)**
Moments of Translation	"These [four] moments constitute the different phases of a general process called translation, during which the identity of actors, the possibility of interaction and the margins of manoeuvre are negotiated and delimited".	Callon 1984: 203
Obligatory Passage Point	"[P]roblematization possesses certain dynamic properties: it indicates the movements and detours that must be accepted as well as the alliances that must be forged." To these ends, an OPP is necessary for describing "a system of alliances, or associations, between entities, thereby defining [their] identity and what they want".	Callon 1984: 206
Problematization	The 1st moment of translation: The process of researchers[43] becoming "indispensable to other actors […] by defining the nature and the problems of the latter and then suggesting that these would be resolved if the actors negotiated the 'obligatory passage point' of the researchers' programme of investigation".	Callon 1984: 196

[43] For the purposes of this framework, I interpret 'researchers' in the broadest sense of the word: Individuals engaged with "investigation or experimentation aimed at the discovery and interpretation of facts", be they economist, engineer, manager or other (see the Merriam-Webster Dictionary definition of research: https://www.merriam-webster.com/dictionary/research – retrieved May 27, 2020).

Sensitizing concept	**Definition**	**Exponents (considered here)**
Referential Alignment	A term "develop[ed] to characterize the quality of referential relationships that enables knowledge artefacts and processes to refer back and forth between different material, organizational, local and temporal settings".	Bates and Juhl 2020: 196
(Re)writing Devices	Through methods of successive adjustment, they establish and transform systems of collective action. They define necessary actions and enable a progressive expression of demands that are only partially undetermined – making these complex systems of action manageable without limiting them.	Callon 2002: 193
Staging	"By considering the inclusion or exclusion of actors, material and symbolic objects and concerns in a space and the construction of boundaries defining the space, staging provides the conditions of possibilities for network translation and formation to happen".	Clausen et al. 2020 (forthcoming) Clausen and Yoshinaka 2007 Clausen and Yoshinaka 2009
Translation	"The repertoire of translation is not only designed to give a symmetrical and tolerant description of a complex process which constantly mixes together a variety of social and natural entities. It also permits an explanation of how a few obtain the right to express and to represent the many silent actors of the social and natural worlds they have mobilized".	Callon 1984: 224 Latour 1987 Latour 2005 Law 2009

6. CONCLUSION AND REFLECTIONS

This dissertation takes root in my ongoing 15-years of experience as a technology manager and engineer in the off-highway mobile hydraulic industry. The research question, **how staging with objects can contribute to managing technological innovation across specialized knowledge networks**, was developed as a response to my limited understanding of my *own* practice in defining, communicating and implementing technical minutia into the wider organizations of which I am a part (however peripherally or temporarily). Unable to recognize these everyday challenges in a mostly prescriptive body of 'innovation management' scholarship purporting to service industrial managers and engineers, I sought answers in science and technology studies, which provided me with a rich vocabulary to address issues of technical expertise. Still – and in contrast to the framework developed in Chapter 5 – this rich body of scholarship includes only a limited focus on the *actionability* of these arguments for industrial practitioners. To remedy these practical shortcomings, I instigated and developed a PhD position from which I could conduct STS research beside (and as a supplement to) my full-time position of technology manager and engineer – as *auto-ethnographer*. In addition to extensive access to, and in-depth involvement with, a diversity of empirical materials, this auto-ethnographic method provided me with opportunities to experiment with theoretical conceptualizations from STS in a variety of engineering contexts within which I carry out my work as a manager and engineer, to reflect over the usefulness of these conceptualizations with colleagues, and to ultimately design a methodological framework for 'staging with objects' *as* an industrial practice that answers the research question in the context of three key dimensions of this practice:

1. **Facilitating engagement across specialized networks**
2. **Fostering common points of reference and alignment of interests across diverse stakeholders, and**
3. **Helping actors to articulate and mobilize resources within their organizations.**

The framework presented here is *not* prescriptive. It is better viewed as a mediating instrument through which practitioners can identify and analyze possible means of action in spaces of technology development *on-the-fly*, that they might actualize such means by way of constituting, configuring and transforming (i.e. *staging*, Clausen and Yoshinaka 2009) objects. One could also call the framework a *provoking dialogic instrument* – where 'dialogue' is defined as any reciprocal interaction between human and non-human actors (see Cooren 2010). Thus, the first output of this dissertation is an *ontological* contribution. Most management tools purporting to serve processes of innovation are limited to epistemological considerations, á la how managers and engineers obtain knowledge and leverage this knowledge in action. Questions or even viewpoints pertaining to the nature of the realities within which these actors operate are mostly considered tangentially – discussing what 'good' *management* or *innovation* are or provide in assumedly transparent contexts – if at all. Instead, the methodological framework presented in Chapter 5 takes root in assumptions that epistemological considerations – regarding the *means* by which technology managers and engineers can know or act – are inseparable from ontological considerations about how things are manifested and associated. With outset in the *skilled practice* of 'managing' and 'engineering' in industrial contexts, the framework introduces a variety of material-semiotic tools, sensibilities and methods from ANT (see Law 2009) to provide practitioners with *means* to: 1) *identify* and *understand* the webs of associations within which they find themselves, and 2) *facilitate* possible and relevant actions to accommodate these associations in *real-time.* Although these aspects of *staging with objects* are mutually shaping, they are considered here individually, as separate contributions of the framework.

6.1. CONCEPTS OF OBJECTS *FOR* INDUSTRIAL PRACTICE

The first contribution of the framework is rooted in concepts of objects from STS that can support practitioners in ascertaining the intentions and scope of the *associations* that comprise their work arrangements in processes of technology development. Previous STS scholarship has shown the framework's four conceptualizations of objects– *boundary objects*, *intermediary objects*, *(re)writing devices* and *calculative devices* – adept in making sense of different types of specific work arrangements. What makes this framework novel is the *localization* of where and how this sensemaking process takes place. Moving beyond academic utilizations of these concepts to analyze and understand empirical material (i.e. how specific realities took form) *after action takes place*, this dissertation presents that these same concepts can be utilized by skilled practitioners to analyze and ultimately shape specific industrial realities (i.e. processes of technology development) *during action.*[44] Findings supporting this include that the *specificity* of these object-conceptualizations provides a sort of map or guide through which technology managers and engineers can establish their position in relation to other key actors and objects in the development space and thus *navigate* intentions that are not always immediately apparent or acknowledged. For example, identifying a test-setup as a boundary object (BO) informs the practitioner about a very specific type of work arrangement (where the object must remain applicable and recognizable across multiple sites of utilization). This makes the BO particularly useful as an object for fostering common points of reference and aligning interests across diverse stakeholders. This is true for practitioners creating new BOs, which once complete don't have to be renegotiated at their different points of application. But it is also true when they utilize established BOs, as these foster compatibility and relevancy between worlds without the need for *direct interaction*

[44] This is a bastardized application of Callon's *generalized symmetry* (1984).

and the unforeseen or de-stabilizing negotiations this can bring. Likewise, the intermediary object (IO) concept provides a means for practitioners to not only trace and analyze the intentions and results of complex networks of associations following (un)successful mobilizations, but provides them with a means of reflection through which they can plan *for*, *around* and *with* the objects in the development space. By asking themselves when and how objects meant to *commission* action can betray initial intentions and become *mediating*, or how supposedly mediating objects, meant to foster multi-sided collaboration, lock specific actors into commissioned roles – before or during these mobilizations – actors can identify taken for granted (or otherwise invisible) assumptions or requirements and develop strategies to accommodate them. As instruments for long-distance control, (re)writing devices and calculative devices will foster different considerations for industrial practitioners. That both conceptualizations take outset in 'centers of calculation' and aim to support cycles of accumulation through which points become centers 'by acting at a distance on many other points' (Latour 1987), engaging with these concepts can sensitize attention towards *associations* that enable agents to control and manage complex systems of action, *without* necessarily reducing or limiting the complexity of these systems. Still, there are important differences between (re)writing devices and calculative devices which make them useful for staging with objects in differing contexts. In their simplest sense, (re)writing devices are texts which reciprocally document and shape observations and results within collective systems of action. In industrial practice, such texts (like engineering reports, standard operating procedures and even process models) expand as they ingest material. Here, new findings are associated in growing, however well-structured, repositories of information (texts) from which *instructions for action* evolve. This continuous process of revision makes them difficult to black-box. They must be re-opened and amended with every new association – if only to record *instructions for acting with* the association. For lack of a better word, industrial (re)writing devices can be described as 'expansive'. According to Callon (2002), (re)writing devices support organization in locations between 'knowing and acting'. This makes (re)writing devices an especially useful concept for practitioners during actions which are focused on *how* a technology is defined in development processes, and where the expected criteria for a technology's performance are still being articulated and revised. In counterpoint calculative devices are *instruments for* black-boxing associations. Calculative devices are solely purposed with reducing the collective production and dissemination of results into new entities that can leave the calculative space and carry its intentions without needing to bear all the elements shaping these intentions with it. Such devices (e.g. *Technology Readiness Levels*, *Failure Mode and Effects Analysis*, *Risk Scoreboards* and *Technology Forecasting*) are widespread in industrial contexts and play important roles in technology development. Identifying and understanding these management tools as processes of network-stabilization and black-boxing enables practitioners to develop rational strategies *around* and *for when* or *how* calculative results are *closed* or *opened*. This is not insignificant because such results are often incorporated into *decision-making gates* or *milestones* that shape and pace the work arrangements of a technology development space. As a 'device of interessement' calculative devices also 'lock' a variety of actors and objects into roles supporting calculative tasks. An awareness of this process allows practitioners to *identify* and make conscientious choices *about* this 'locking-in' process and its consequences when negotiating the articulated 'facts' of a development space and the problematizations they engender.

6.2. *STAGING WITH OBJECTS* AS AN INDUSTRIAL PRACTICE

In addition to assisting technology managers and engineers in *identifying* and *understanding* the webs of associations within which they find themselves, the four object conceptualizations from STS can aid practitioners in *constituting, configuring* and *transforming* these associations through the objects they manifest and situate. The second contribution of the framework, 'staging', can assist practitioners in *facilitating* and *executing* possible and relevant actions to accommodate these associations. These findings take root in auto-ethnographic studies of technology development at a global leader in the off-highway mobile hydraulic industry. The empirical material supporting these findings stems from two cases representing different types of industrial technology development – both of which were led by me over periods exceeding 20 months and entrenched in endeavors within which I have participated or led over my 15 years of employment at the host company. The first case follows a company devised technology as it was matured through interactions with and towards the general market in which the company competes. The second case follows an industrial-academic collaboration around the validation and development of a potential replacement for the hydraulic lubricant dominating the industry. Principle findings concerning *staging* with objects *as* industrial practice follow here.

- The 'three key dimensions' of *staging with objects* (facilitating engagement across specialized networks; fostering common points of reference and alignment of interests across diverse stakeholders; and helping actors to articulate and mobilize resources within their organizations) were shown to address principle aspects of technology development – where different empirical material from both cases was used interchangeably to consider each dimension (see Chapters 4 and 5). This also demonstrates the mutually shaping aspects of these key dimensions and the need to address them simultaneously.

- *Means of action* within a development space will utterly depend upon the reading and navigation of the situation in which a practitioner finds themselves and the (assumed) potential of the objects at hand. This makes identifying and understanding relationships between *objects* and the overall *objectives* of the technology development space a principle characteristic of staging with objects (see Chapters 4 and 5).

- The positions of actors and their objects are reciprocally altered as they re-positioned to navigate changing situations. Thus, the agency to situate and define objects is a complex process of negotiation and does not reside in a single actor. This necessitates conscious reflection over how objects are accepted, contested and changed in interaction with different perspectives (Bates 2020a, forthcoming. See also Bates and Clausen 2020; Bates and Juhl 2020).

- Staging with objects requires increased attention to how objects perform across intentional (commissioning) and unpredictable (mediating) roles. This necessitates conscious reflection over how objects are accepted, contested and changed in interaction with different perspectives (Bates 2020a, forthcoming. See also Bates and Clausen 2020; Bates and Juhl, forthcoming 2020).

- Attention to processes of staging with objects can help technology managers and engineers articulate and accommodate fluid demands from top management teams who set overarching objectives, exercise control over resources, and provide mandates for action, but are otherwise not directly involved in solving technical issues in translations from invention to commercialization (Bates 2020a, forthcoming: 189).

- Viewing 'commercialization criteria' as products of ongoing negotiations between diverse actor-networks can provide more effective strategies (means of action) than viewing these criteria as stable, punctualized entities that guide how a technology is developed (Bates 2020a, forthcoming: 189. See also Bates and Juhl, forthcoming 2020).

- Keeping objects *open* – not 'black-boxing' them prematurely – seems to support all three of the key dimensions. Still, the challenges of this endeavor should not be underestimated. Stable black-boxed entities can migrate between networks in ways that instable entities can't. Moreover, expressing the complexities of technology development into single digit or milestone (á la TRL or NPD process models) enables a diversity of stakeholders to make agreements about a technology without necessarily understanding the *complex technicalities* upon which it rests. Could for example, a focus on the *production of agreement*s (i.e. 'matters of concern') through which these digits or milestones are stabilized – as opposed to the relentless pursuit of *stable* digits and milestones for pacing industrial technology development – foster incentives for keeping objects open? (see Chapter 4).

- Decision-making tools (like NPD process models or the TRL figure of merit) take for granted that technical competencies and insights are readily available for selection, promotion and control. Such assumptions downplay the role of 'technical acuity', which enabled case participants to *re-open* 'closed objects' – and ultimately *re-define* and *re-adjust* the shared components of which the objects were comprised – when faced with the de-stabilization of, or disassociation between, principle objects (see Chapter 4).

- From a staging perspective, 'referential alignment' is a process of aligning material configurations in order to ensure that observations produced in one setting can be reproduced and understood in other settings. How practitioners address local specificities within these settings thus becomes a material condition for how they understand knowledge (i.e. the facts these specificities generate) and the conditions for its applicability (see Chapter 4; Bates and Juhl 2020; Juhl and Bates 2020)

The following subsection considers the limitations and implications of these principle findings and personal challenges pertaining to their realization.

6.3. REFLECTIONS

Perhaps the most important implication of this dissertation for industrial practice, is the assumption that a methodological framework with a high degree of *theoretical* abstraction can serve *practicing* technology managers and engineers with limited exposure to the social sciences or humanities. I consistently met preconceptions contrary to this assumption when discussing my research at conferences, university stays or PhD-courses, where voiced concerns included variations on 'real' engineers lacking adequate powers of self- or philosophical reflection to accommodate 'advanced' ontological considerations. Interestingly, this was never a concern for engineers employed in the spaces of technology development and with whom I discussed and developed the framework. Although the STS vocabulary and ontologies were new for the participants, the ways by which different *associations* can make the same *actors* and *objects* essential or superfluous – where a 20-micron tolerance on a 4 cm^3 component can stop production or render a 10-ton tractor useless for a specific application – are realities that case participants address every day. 'Non-human agency' seemed to resonate with their own experiences and was not a difficult concept for them to grasp. That these STS conceptualizations were being presented to case participants on-the-fly by someone *intimately* familiar with their industrial practice and in the context of their work arrangements should probably not be overlooked as abetting their comprehension by the participants.

Such considerations are also closely tied to the relevance of the framework for other contexts of industrial technology development. Although the (mostly ANT based) ontology upon which the framework rest was initially foreign for most of the participants, the development of the framework was rooted in their own technical realities. As Vinck (2009: 1) has also observed, such a focus can enable a "different vision of technology [to] emerge – a vision that technicians should find easy to understand because it will be based on their day-to-day life". That the framework was specifically designed to address challenges of skilled practitioners within spaces of technology development is perhaps the best explanation for its efficacy in abetting technology managers and engineers to facilitate engagement across specialized networks, foster common points of reference and alignment of interests across diverse stakeholders, and help actors to articulate and mobilize resources within their organizations.

The *cases* considered are limited to the activities of a global leader in the off-highway mobile industry. Still, the *objects* considered – NPD process models, simulations, the TRL figure of merit, standards and specifications, prototypes, and test-setups – are ubiquitous in industrial firms. Perhaps the *intricacies* of these objects would differ in the toy-making, food-processing, pharmaceutical or petrochemical industries, but *associations* between these objects would be similar if not identical. With its focus on associations this framework provides a way for technology managers and engineers to reflect over technology development as a process of mediation occurring through and with a variety of objects. Ideally, such reflections will foster greater sensitivity to the *management tools* that pace these processes of industrial technology development at a macro-level, as well as the *sociotechnical minutiae* shaping the micro-processes of development to which they are specifically tasked. Ontological considerations regarding, agency, associations and different conceptualizations of objects can also provide a greater awareness of their own strategic opportunities for *designing* processes of technical development by engaging, enrolling and aligning other networks – while taking the precariousness of these endeavors seriously. In a recent review of one of the papers supporting this dissertation (Bates and Clausen 2020), Mody (2020) praised the scope of our auto-ethnographic endeavor and argument:

> That some STS concepts have near-equivalents in [industrial] members' vocabularies in many sites of technical work, and therefore that there should be plenty of scope for two-way traffic: STS needs to understand members' vocabularies, but members – engineers, technicians, managers, etc. – can benefit from engaging with STSers' vocabulary (ibid: 2-3).

Still, there are certainly a variety of situations where this approach would be more appreciated than others. In relatively flat organizations with traditions for employee participation and empowerment (traditions towards which the host company strives), it is likely that *staging with objects* to develop and stabilize cross-functional networks across diverse organizations would be appreciated – as in the case here. Even so, and regardless of the organizational structure in which they find themselves, the *autonomy* of technology managers and engineers will always be bounded, either by constraints to *time* (e.g. how long the project can run) and *finances* (e.g. internal budgets and external market forces), or as to how extensive a network can become *before* its architects lose control over its constitution, configuration or translation. Moreover, repeated and successful manipulations of objects and people by any individual actor might be considered outright *disempowering* or *nonparticipatory.* In more hierarchical organizations, it is perhaps less likely that actors 'manipulating' objects to perform in associations *outside* of their recognized or sanctioned gamut would be appreciated. On the other hand, if these strategic manipulations of objects can be demonstrated as positive endeavors (e.g. because they generate results quickly or maximize cross-functional cooperation on resources), then the possible qualms of top management within such organizations might be mitigated – or even eliminated. These considerations aside, it is important to note that this dissertation *does* demonstrate the application of *staging with objects* within an international organization and empirical contexts that also include top-down power plays and bureaucratic elements that are not particularly participatory nor empowering. Viewing organizations as complex networks of initially unconnected entities, converging under certain conditions that contribute to making these connections more or less robust (Hernes 2010), indicates that a technology development practice rooted in how associations are manifested and maintained will *ideally* transcend the more or less hierarchical structures of the organizations where it is employed.

In papers supporting this dissertation (Bates 2020a, forthcoming; Bates and Clausen 2020) I make appeals for other technology managers and engineers to pursue similar auto-ethnographic research on industrial practice. Accommodating this plea could be more complicated than initially proposed. One could argue that the 'autonomous self-development' encouraged by the host company played a significant role in making my research possible and that a technology manager with similar responsibilities to my own may not be allowed to take on another full-time job as Industrial PhD fellow (at their own behest) in many companies. Still, there are formal infrastructures in place to support this type of research – at least in Scandinavia – and of which my Industrial PhD Fellowship is an example. It is not certain that engineers *unschooled* in auto-ethnography could master the analytic methods employed in this dissertation to develop similar frameworks. Still, the training and practice in '-graphy' from my previous engineering experience did certainly prepare me for the often-frantic practice of designing, analyzing and documenting my own work. Graphical and textual representations are a cornerstone of engineering practice (Blanco 2009; Laureillard and Vinck 2009; Reverdy 2009). Possibly the most difficult aspect of my auto-ethnographic research agenda was accommodating the duality of my practitioner-analyst role. Although I discussed STS theory regularly with other case participants (and despite 'academic knowledge' to the contrary), it was easy to revert to simple views of my practice feeding my analyses (i.e. practitioner→analyst). This was particularly true when working under pressure. But in tack with increasing inquiries from participants regarding my own *theoretical* takes on our development activities, this academic knowledge seemed to finally 'take hold' and the mutual shaping of these roles (i.e. practioner↔analyst) became the *de facto* perception of my work for both the case participants and myself. Hayano (1979: 99) submits that "auto-ethnography is not a specific research technique, method, or theory, [rather] it colors all three as they are employed in fieldwork". It is only recently that I have understood how aptly this simple citation describes the scope of my research. Drawing on hindsight, and a painting metaphor, auto-ethnography was like dipping a thick wet brush into watercolor paints and watching haplessly as colors spread over the lines separating academic-scholarship and engineering-practice at their point of application – before finally rendering many of these lines invisible. This dissertation represents efforts to re-trace these lines using a smaller dryer brush.

This brings me back the final methodological concern stipulated in the eighth characteristic of BOAP: "Attend to the detailed dynamics of sociotechnical change both empirically and theoretically" (Hyysalo et al. 2019: 8). To this end, the five papers of the appendix utilize object-conceptualizations from STS to describe different aspects of sociotechnical change as these were observed in empirical material stemming from my own skilled practice as a technology manager and engineer. Within these papers, I endeavored to strike a balance between the technical minutia necessary for understanding the practice of managing technology development, and the analytic rigor of STS scholarship – to demonstrate that the *same* object-conceptualizations used to analyze coordinative action at universities can assist technology managers and engineers in understanding and improving the nature of their own skilled practice in industry .

7. BIBLIOGRAPHY

Adler, P. A., and Adler, P. (1987). *Membership Roles in Field Research. Qualitative Research Methods Series* (Vol. 6). Thousand Oaks, CA: Sage.

American Academy of Arts & Sciences. (2016). *Public Research Universities. Recommitting to Lincoln's Vision: An Educational Compact for the 21st Century*. Cambridge, MA: American Academy of Arts & Sciences. Retrieved July 26, 2020, from https://www.amacad.org/sites/default/files/publication/downloads/PublicResearchUniv_Recommendations.pdf.

Akrich, M., Callon, M., Latour, B., and Monaghan, A. (2002). The key to success in innovation part I: The art of interessement. *International Journal of Innovation Management,* 6(02), 187-206.

Akrich, M., Callon, M., Latour, B., and Monaghan, A. (2002). The key to success in innovation part II: The art of choosing good spokespersons. *International Journal of Innovation Management*, 6(02), 207-225.

Anderson, L. (2006). Analytic autoethnography. *Journal of Contemporary Ethnography*, 35(4), 373-395.

Anderson, L. (2011). Time is of the essence: An analytic autoethnography of family, work, and serious leisure. *Symbolic Interaction*, 34(2), 133-157.

Anderson, L., and Taylor, J. D. (2010). Standing out while fitting in: Serious leisure identities and aligning actions among skydivers and gun collectors. *Journal of Contemporary Ethnography*, 39(1), 34-59.

Andreasen, M. M., Hansen, C. T., and Cash, P. (2015). *Conceptual Design: Interpretations, Mindset and Models*. Cham, Switzerland: Springer.

Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C. M., Bates, C. A. (2018a). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109794B4.

Arbjerg, N., Ennemark, P., Frederiksen, M., Olesen, C. M., and Bates, C. A. (2018b). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109801B4.

Artto, K., Kulvik, I., Poskela, J., and Turkulainen, V. (2011). The integrative role of the project management office in the front end of innovation. *International Journal of Project Management*, 29(4), 408-421.

Baarts, C. (2015). Autoetnografi. In S. Brinkmann and L. Tanggaard (eds.), Kvalitative Metoder, En grundbog. Copenhagen: Hans Reitzel Forlag, 169-180.

Barad, K. (2003). Posthumanist performativity: Toward an understanding of how matter comes to matter. *Signs: Journal of Women in Culture and Society*, *28*(3), 801-831.

Bates, C.A. (2008). An Estimation Model for Finding Failure Time Distributions of Gear-wheels. In *Proceedings of 2008 Symposium i Anvendt Statistik*. Copenhagen, Denmark: Copenhagen Business School and Danmarks Statistik. January 28-30, 2008.

Bates, C. A. (2014). A method of comparing recurring observations of leakage in rotary shaft seals under accelerated tests. In *Proceedings of the 18th International Sealing Conference*. Stuttgart. Germany: University of Stuttgart and VDMA. October 8-9 2014.

Bates, C.A. (2020a, forthcoming). Staging with objects: Translation from technology to product development. In C.Clausen, D.Vinck, S.Pedersen, and J.Dorland (eds.) *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach.* Cheltenham: Edward Elgar Publishing.

Bates, C.A. (2020b, under review). Positioning Patents to Perform Coordinative Action in Industrial Technology Development. *STS Encounters*.

Bates, C. A., Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C. M. (2018a). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109795B4.

Bates, C. A., Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C. M. (2018b). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109796B4.

Bates, C. A., Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C. M. (2018c). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109798B4.

Bates, C. A., Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C. M. (2018d). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109799B4.

Bates, C. A., Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C. M. (2018e). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109800B4.

Bates, C. A., Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C. M. (2018f). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109803B4.

Bates, C.A., Broe-Richter, H. W., Bendlin, C. R., and Ennemark, P. (2020). Case study: The effect of an amorphous hydrogenated carbon-coated gear-wheel on a hydraulic orbital motor's efficiency over time. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 234(3), 320-333.

Bates, C. A., and Clausen, C. (2020). Engineering Readiness: How the TRL Figure of Merit Coordinates Technology Development. *Engineering Studies*, 12(1), 9-38.

Bates, C.A., and Juhl, J. (2020, forthcoming). Staging referential alignment in industrial-academic collaboration. In C.Clausen, D.Vinck, S.Pedersen, and J.Dorland (eds.), *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach.* Cheltenham: Edward Elgar Publishing.

Becker, H.S. (1951) The Professional Dance Musician and His Audience. *American Journal of Sociology,* 57 136–144.

Bender, V. (2004). *Danfoss Hydraulik Gennem 40 år*. Nordborg: Danfoss A/S.

Björling, M. and Shi, Y. (2019). DLC and Glycerol: Superlubricity in Rolling/Sliding Elastohydrodynamic Lubrication. *Tribology Letters,* 67: 23.

Blanco, E. (2009). A Prototype Culture: Designing a Paint Atomizer. In D. Vinck (ed.), *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press, 119-133.

Bloor, D. (1976). *Knowledge and Social Imagery*. London: Routledge & Kegan Paul.

Bonner, J.M., Ruekert, R.W., and Walker Jr., O.C. (2002). Upper management control of new product development projects and project performance. *The Journal of Product Innovation Management*, 19, 233–245.

Borg, M., Badr, I., and Royle, G. J. (2012). The use of a figure-of-merit (FOM) for optimisation in digital mammography: a literature review. *Radiation Protection Dosimetry*, 151(1), 81-88.

Bovy, M., and Vinck, D. (2009). Social Complexity and the Role of the Object: Installing Household Waste Containers. In D. Vinck (ed.), *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press, 54-75.

Bowen, G. A. (2006). Grounded theory and sensitizing concepts. *International Journal of Qualitative Methods,* 5(3), 12-23.

Bowker, G., and S. L. Star, 1999. *Sorting Things Out: Classification and its Consequences*. Cambridge, MA: MIT Press.

Broberg, O., Andersen, V., and Seim, R. (2011). Participatory ergonomics in design processes: The role of boundary objects. *Applied Ergonomics*, 42(3), 464-472.

Brønnum, L. (2017). Strategic Enactment of Front End Innovation: *A Case Study of Multiple Enabling Opportunities*. Aalborg Universitetsforlag. PhD Series, Technical Faculty of IT and Design, Aalborg University,Denmark.

Callon, M. (1984). Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay. *The Sociological Review*, 32(1_suppl), 196–233.

Callon, M. (1991). Techno-Economic Networks and Irreversibility. *A Sociology of Monsters: Essays on Power, Technology, and Domination*, 277-303.

Callon, M. (2002). Writing and (Re)writing Devices as Tools for Managing Complexity. In J. Law, and A. Mol (eds.) *Complexities: Social Studies of Knowledge Practices.* Durham: Duke University Press, 191-217.

Callon, M. (2004). The role of hybrid communities and socio-technical arrangements in the participatory design. *Journal of the Center for Information Studies*, (5), 1-10.

Callon, M., and Muniesa, F. (2005). Peripheral vision: Economic markets as calculative collective devices. *Organization Studies*, 26(8), 1229-1250.

Callon, M., and Rabeharisoa, V. (2003). Research “in the wild” and the shaping of new social identities. *Technology in Society*, 25(2), 193-204

Cartwright, N. (1999). Nomological machines and the laws they produce. In *The Dappled World: A study of the Boundaries of Science.* Cambridge: Cambridge University Press, 49-74.

Christiansen, J. K., and Varnes, C. J. (2007). Making decisions on innovation: meetings or networks?. *Creativity and Innovation Management*, 16(3), 282-298.

Clausen, C., and Gunn, W. (2015). From the social shaping of technology to the staging of temporary spaces of articipatory innovation – A case of participatory innovation. *Science and Technology Studies*, 28(1), 73-94.

Clausen, C., Pedersen, S., and Yoshinaka, Y. (2012). Facilitating and navigating user knowledge in an organizational context. In *Proceedings of the 12th Participatory Design Conference Association for Computing Machinery*, 41-45.

Clausen, C., and Yoshinaka, Y. (2005). Sociotechnical spaces: Guiding politics, staging design. *International Journal of Technology and Human Interaction (IJTHI)*, 1(3), 44-59.

Clausen, C., and Yoshinaka, Y. (2007). Staging socio-technical spaces: Translating across boundaries in design. *Journal of Design Research*, 6(1-2), 61-78.

Clausen, C., and Yoshinaka, Y. (2009). The Role of Devices in Staging Front End Innovation. In *Proceedings of the First International Conference on Integration of Design, Engineering and Management for Innovation IDEMI09*. Porto: FEUP Faculty of Engineering and Management of the University of Porto, 1-8.

Clausen, C. Vinck, D., Dorland, J., and Pedersen S. (eds.). (2020, *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach*. Cheltenham: Edward Elgar Publishing.

Pedersen, S., Dorland, J., and Clausen, C., (2020, forthcoming). Staging – from theory to action. In C. Clausen, D. Vinck, S. Pedersen, and J. Dorland (eds.), *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach.* Cheltenham: Edward Elgar Publishing.

Conway, S., and Steward, F. (2009). *Managing and Shaping Innovation*. Oxford: Oxford University Press.

Cooper, R.G. (2006). Managing technology development projects. *Research-Technology Management*, 49(6), 23-31.

Cooper, R.G. (2008). Perspective: The Stage-Gate® idea-to-launch process—Update, what's new, and NexGen systems. *Journal of Product Innovation Management*, 25(3), 213-232.

Cooren, F. (2010). *Action and agency in dialogue: Passion, Incarnation and Ventriloquism* (Vol. 6). Amsterdam: John Benjamins Publishing.

Cooren, F., and Sandler, S. (2014). Polyphony, ventriloquism, and constitution: In dialogue with Bakhtin. *Communication Theory*, 24(3), 225-244.

Czarniawska, B. (2014). *Social Science Research: From Field to Desk*. Beverly Hills: Sage.

Danfoss A/S (2020a). *Annual Report 2019*. Nordborg: The Danfoss Group.

Danfoss A/S (2020b). *Propriety Company PowerPoint Presentation*. Nordborg: The Danfoss Group.

Ennemark, P., Liljenberg, S., Rudolph, T., Tychsen, T., Vester, J. (2016a). *Hydraulic Steering System*. US Patent No. US9950737B2.

Ennemark, P., Liljenberg, S., Rudolph, T., Tychsen, T., Vester, J. (2016b*). Hydraulic Steering System*. US Patent No. US10161425B2.

Eriksen, T. T., Kruse, M., & Larsen, G. (2006). *The Scandinavian Way*. Copenhagen: Copenhagen Institute for Future Studies.

Florén, H., and Frishammar, J. (2012). From preliminary ideas to corroborated product definitions: Managing the front end of new product development. *California Management Review*, 54(4), 20-43.

Frederiksen, M., Ennemark, P., and Olesen, C. M., Arbjerg, N., Bates, C. A. (2019). *Hydraulische Lenkeinheit*. DE Patent No. DE102018112044B3.

Frishammar, J., Lichtenthaler, U. and Richtnér, A. (2013), Key issues in managing process development. *R&D Management*, 43: 213-226.

Furustig, J., Almqvist, A., Bates, C.A., Ennemark, P., and Larsson, R. (2015a). A two-scale mixed lubrication wearing-in model, applied to hydraulic motors. *Tribology International*, 90, 248-256.

Furustig, J., Larsson, R., Almqvist, A., Bates, C.A., and Ennemark, P. (2015b). A wear model for EHL contacts in gerotor type hydraulic motors. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 229(2), 254-264.

Furustig, J., Almqvist, A., Pelcastre, L., Bates, C.A., Ennemark, P., and Larsson, R. (2016). A strategy for wear analysis using numerical and experimental tools, applied to orbital type hydraulic motors. In *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 230(12), 2086-2097.

Garud, R., Gehman, J., and Kumaraswamy, A. (2011). Complexity arrangements for sustained innovation: Lessons from 3M Corporation. *Organization Studies*, 32(6), 737-767.

Garud, R., Tuertscher, P., and van de Ven, A.H. (2013). Perspectives on Innovation Processes, *The Academy of Management Annals*, 7:1, 775-819,

Gish, L., & Clausen, C. (2013). The framing of product ideas in the making: A case study of the development of an energy saving pump. *Technology Analysis & Strategic Management*, 25(9), 1085-1101.

Hansen, P.R. and Clausen, C. (2017): Management concepts and the navigation of interessement devices: The key role of interessement devices in the creation of agency and the enablement of organizational change, *Journal of Change Management*, DOI:10.1080/14697017.2017.1286515.

Haraway, D. (1988/2007). Situated knowledges: The science question in feminism and the privilege of partial perspective. In K. Asdal, B.Brenna and I. Moser (eds), *Technoscience: The Politics of Intervention*. Oslo: Oslo Academic Press, Unipub AS, Norway, 109-131.

Hayano, D.M. (1977). The professional poker player: Career identification and the problem of respectability. *Social Problems*, 24(5), 556-564.

Hayano, D.M. (1979). Auto-ethnography: Paradigms, problems, and prospects. *Human Organization*, 38(1), 99-104.

Hayano, D.M. (1980). Communicative competency among poker players. *Journal of Communication*, 30(2), 113-20.

Hayano, D.M. (1982). *Poker faces: The life and work of professional card players*. Oakland: University of California Press.

Hernes, T. (2010). Actor-Network Theory, Callon's Scallops and Process-Based Organization Studies. In T. Hernes and S.Maitlis (eds.), *Process, Sensemaking and Organizing*. Oxford: Oxford University Press, 161-184.

Herstatt, C., Verworn, B., and Nagahira, A. (2004). Reducing project related uncertainty in the" fuzzy front end" of innovation: A comparison of German and Japanese product innovation projects. *International Journal of Product development*, 1(1), 43-65.

Hussenot, A., and Missonier, S. (2010). A deeper understanding of evolution of the role of the object in organizational process: The concept of 'mediation object'. *Journal of Organizational Change Management*, 23(3), 269-286.

Hyysalo, S. (2010) *Health Technology Development and Use: From Practice Bound Imagination to Evolving Impacts*. London: Routledge.

Hyysalo, S., Pollock, N., and Williams, R. (2019). Method matters in the social study of technology: Investigating the biographies of artifacts and practices. *Science and Technology Studies*. 32, 2-25.

Ingold, T. (2012). Toward an ecology of materials. *Annual Review of Anthropology*, 41: 427-442.

Ingold, T. (2014). That's enough about ethnography! *HAU: Journal of Ethnographic Theory,* 4 (1): 383–395.

Jensen, A.R.V., Clausen, C., and Gish, L. (2018). Three perspectives on managing front end innovation: process, knowledge, and translation. *International Journal of Innovation Management*, 22, (7), 1850060.

Juhl, J. (2013). *Models in Action: Realising Abstractions. Doctoral Dissertation*. Aalborg: Aalborg Universitetsforlag.

Juhl, J. (2016). Innovation science: between models and machines. *Engineering Studies,* 8(2), 116-139.

Juhl, J., and Buch, A. (2018). Engineering-Business: The co-production of institutions, skills and engineering challenges. In S.H. Christensen, B. Delahousse, C. Didier, M. Meganck, and M. Murphy, *The Engineering-Business Nexus.* London: Springer Science + Business Media B.V, 449-473

Juhl, J., And Buch, A. (2018). The role of education in academic ecosystems. In B. Lund And S. Arndt (eds.),*The Creative University*. Contemporary Responses To The Changing Role Of The University.Leiden: Brill Sense, 102-118.

Juhl, J., and Bates, C.A. (2020, working paper). Referential Alignment: Situating Knowledges and Materialities in Innovation Science. To be Decided.

Juhl, J., and Lindegaard, H. (2013). Representations and visual synthesis in engineering design*. Journal of Engineering Education*, 102(1), 20-50.

Jørgensen, U. (2004). The design engineers of the future have innovative competences. *Produktudviklingsdagen 2004*, IPU, Technical University of Denmark.

Koch, C. (2000). The ventriloquist's dummy? The role of technology in political processes. *Technology Analysis & Strategic Management*, 12:1, 119-138.

Koen, P., Ajamian, G., Burkart, R., Clamen, A., Davidson, J., D'Amore, R., ... and Karol, R. (2001). Providing clarity and a common language to the "fuzzy front end". *Research-Technology Management*, 44(2), 46-55.

Kuhn, T. S. (1962). *The Structure of Scientific Revolutions*. Chicago: Chicago University Press.

Larsen, S. (2017). Universiteterne er dybt afhængige af overheadpenge. *Sciencereport.dk*. Retrieved July 26, 2020, from https://sciencereport.dk/samfund/universiteterne-afhaengige-overheadpenge/.

Laureillard, P., and Vinck, D. (2009). The role of graphical representations in inter-professional cooperation. In D. Vinck (ed.), *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press, 160-175.

Latour, B. (1987). *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge: Harvard University Press.

Latour, B. (2004a). *Politics of Nature: How to Bring the Sciences into Democracy*. Cambridge, MA: Harvard Univ. Press

Latour, B. (2004b). Why has critique run out of steam? From matters of fact to matters of concern. *Critical Inquiry* 30, no. 2, 225-248.

Latour, B. (2005). *Reassembling the Social: An Introduction to Actor-Network-Theory*. Oxford: Oxford University Press.

Latour, B. (2008). *What is the style of matters of concern: Two lectures in empirical philosophy*. Department of Philosophy, University of Amsterdam. Spinoza Lectures. Assen : Koninklijke Van Gorcum.

Law, J. (1984) On the methods of long-distance control: Vessels, navigation and the Portuguese route to India. *The Sociological Review*, 32: 234–263.

Law, J. (1987). Technology and heterogeneous engineering: The case of Portuguese expansion. In W.E.Bijker, Hughes, T.P., and T.Pinch (eds.), The *Social Construction of Technological Systems: New Directions in* *the Sociology and History of Technology, Anniversary Edition*. Cambridge, MASS: MIT Press, 105-128.

Law, J. (2002). On hidden heterogeneities: complexity, formalism and aircraft design. In J. Law and A. Mol (eds.), *Complexities: Social Studies of Knowledge Practices*. Durham, North Carolina: Duke University Press, 116-141.

Law, J. (2009). Actor Network Theory and Material Semiotics. *The new Blackwell Companion to Social Theory*. Hoboken: Blackwell Publishing Ltd, 141-158.

Law, J. (2019). Material semiotics. Retrieved July 26, 2020, from *www.heterogeneities.net/publications/Law2019MaterialSemiotics.pdf*.

Lee, C. F., and Amjadi, M. (2014). The role of materiality: Knowing through objects in work practice. *European Management Journal*, 32(5), 723-734.

Legardeur, J., Boujut, J.F. and Tiger, H. (2010). Lessons learned from an empirical study of the early design phases of an unfulfilled innovation. *Res Eng Design* 21, 249–262. DOI: 10.1007/s00163-010-0090-5.

Looy, B. V., Debackere, K., & Andries, P. (2003). Policies to stimulate regional innovation capabilities via university–industry collaboration: an analysis and an assessment. *R&D Management*, 33(2), 209-229.

Mahoney, J. V., Blomberg, J. L., Trigg, R. H. and Shin, C.K. (1999). *System for searching a corpus of document images by user specified document layout components*. US Patent No. US5999664A.

Mankins, J. C. (2009). Technology Readiness and Risk Assessments: A New Approach. *Acta Astronautica* 65, no. 9-10, 1208-1215.

Markham, S. K., Ward, S. J., Aiman-Smith, L., and Kingon, A. I. (2010). The valley of death as context for role theory in product innovation. *Journal of Product Innovation Management*, 27(3), 402-417.

Mer, S. (2009). The structural engineer in the design office: A world, its objects, and its work practices. In *Everyday Engineering: An Ethnography of Design and Innovation.* Cambridge: MIT Press, 79-91.

Mody, C. (2020). Normal science in the time of Corona. *Engineering Studies*, 12:1, 1-7.

Narayanamurti, V., and Odumosu, T. (2016). *Cycles of Invention and Discovery.* Cambridge, MA: Harvard University Press.

Olechowski, A., Eppinger, S. D., & Joglekar, N. (2015) Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities. In Proceedings of *2015 Portland International Conference on Management of Engineering and Technology* (PICMET), *Portland, Oregon*, USA. 2-6 August *2015*, 2084-2094.

Osenga, M. (2020) A big deal in hydraulics. *Diesel Progress March 2020*. Phoenix, AZ: KHL Group Americas LLC, 29-32.

Pedersen, S. (2020). Staging negotiation spaces: A co-design framework. *Design Studies*, 68: 58-81.

Phillips, L. (2011). *The Promise of Dialogue: The Dialogic Turn in the Production and Communication of Knowledge.* Amsterdam: John Benjamin's Publishing.

Ravaille, N., and Vinck, D. (2009). Contrasting Design Cultures: Designing Dies for Drawing Aluminium. In D. Vinck (ed.), *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press, 93-117.

Rau, C., Neyer, A. K., and Möslein, K. M. (2012). Innovation practices and their boundary-crossing mechanisms: a review and proposals for the future. *Technology Analysis and Strategic Management,* 24(2), 181-217.

Reid, S.E., and de Brentani, U. (2004). The fuzzy front end of new product development for discontinuous innovations: a theoretical model. *The Journal of Product Innovation Management* 21(3), 170–184.

Reverdy, T. (2003). Writing Procedures: The Role of Quality Assurance Formats. In D. Vinck (ed.), *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press, 137-57.

Russell, S., and Williams, R. (2002). Social shaping of technology: frameworks, findings and implications for policy with glossary of social shaping concepts. In K.H. Sørensen and R. Williams (eds.), *Shaping Technology, Guiding Policy: Concepts, Spaces and Tools*. Cheltenham, UK: Edward Elgar Publishing, 37-132.

Sadin, S. R., Povinelli, F. P., and Rosen, R. (1989). The NASA technology push towards future space mission systems. Acta Astronautica, 20, 93–77.

Shi, Y., Minami, I., Grahn, M., Björling, M., and Larsson, R. (2014). Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants. *Tribology International*, 69, 39-45.

Star, S.L. (1989). The structure of ill-structured solutions: Boundary objects and heterogeneous distributed problem solving. In R. Gasser and M. Huhns (eds.), Readings in *Distributed Artificial Intelligence. Vol 3*. Menlo Park, CA: Morgan Kaufmann, 37-54.

Star, S.L. (2010). This is Not a Boundary Object: Reflections on the Origin of a Concept. *Science, Technology, and Human Values*, *35*(5), 601–617. DOI: 10.1177/0162243910377624.

Star, S.L., and Griesemer, J. R. (1989). Institutional ecology, translations and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, 19(3), 387-420.

Suchman, L., Blomberg, J., Orr, J. E., and Trigg, R. (1999). Reconstructing technologies as social practice. *American Behavioral Scientist*, 43(3), 392-408.

Szajnfarber, Z., and Weigel, A.L. (2013). A Process Model of Technology Innovation in Governmental Agencies: Insights from NASA's Science Directorate. *Acta Astronautica* 84, 56–68.

Stewart, J., and Hyysalo, S. (2008). Intermediaries, users and social learning in technological innovation. *International Journal of Innovation Management,* 12(3), 295–325

Suchman, L., Blomberg, J., Orr, J. E., and Trigg, R. (1999). Reconstructing technologies as social practice. *American Behavioral Scientist*, 43(3), 392-408.

Sønnichsen, O. (2006). *Mulighedernes Mand – en bog om Jørgen Mads Clausen*. Copenhagen: Jyllands-Postens Forlag.

Trevelyan, J. (2010). Reconstructing engineering from practice, *Engineering Studies*, 2:3, 175-195.

Trigg, R. H., Irish, P. M., and Suchman, L. A. (1992). *Automatically creating a second workspace operation record including history data and a unit ID based on a first workspace operation.* US Patent No. US5159669A

Trompette, P. and Vinck, D. (2009). Revisiting the notion of boundary object. *Revue D'anthropologie Des Connaissances*, 3(1), 3-25.

Universities UK. (2016). *University Funding Explained.* London: Universities UK. Retrieved July 26, 2020, from https://www.universitiesuk.ac.uk/policy-and-analysis/reports/Documents/2016/university-funding-explained.pdf.

van de Ven, A.H. (1986). Central problems in the management of innovation. *Management Science*, 32(5), 590–607.

van de Ven, A.H., Angle, H.L., and Poole, M.S. (eds). (1989). *Research on The Management of Innovation: The Minnesota Studies*. New York: Harper and Row.

van de Ven, A.H., & Garud, R. (1989). A framework for understanding the emergence of new industries. In Rosenbloom RS, Burgelman RA (eds.), *Research on Technological Innovation, Management and Policy (Vol. 4).* Greenwich, CT: JAI Press, 195–225.

van de Ven, A.H., Polley D. E., Garud, R., and Venkataraman, S. (1999). *The Innovation Journey.* Oxford: Oxford University Press.

van de Ven, A.H. (2017) The innovation journey: You can't control it, but you can learn to maneuver it. *Innovation*, 19:1, 39-42.

Verworn, B., Herstatt, C., and Nagahira, A. (2008). The fuzzy front end of Japanese new product development projects: impact on success and differences between incremental and radical projects. *R&D Management,* 38(1), 1-19.

Vinck, D. (ed.) (2009a). *Everyday Engineering: An Ethnography of Design and Innovation.* Cambridge: MIT Press.

Vinck, D. (2009b). Introduction. In Vinck, D. (ed.), *Everyday Engineering: An Ethnography of Design and Innovation.* Cambridge: MIT Press, 1-10.

Vinck, D. (2010). *The Sociology of Scientific Work*. Cheltenham: Edward Elgar Publishing.

Vinck, D. (2011). Taking intermediary objects and equipping work into account in the study of engineering practices, *Engineering Studies*, 3:1, 25-44.

Vinck, D. (2012). Accessing material culture by following intermediary objects. In L. Naidoo (ed.), *An Ethnography Of Global Landscapes And Corridors.* Chicago: InTech Publishing, 89-108.

Vinck, D., Jeantet, A., and Laureillard, P. (1996). Objects and other intermediaries in the sociotechnical process of product design: An exploratory approach. In J. Perrin and D.Vinck (eds.),*The Role of Design in the Shaping of Technology.* Luxembourg: Office for Official Publications of the European Communities, 297-320.

Vinck, D., and Tanferri, M. (2020, forthcoming). Taking the metaphor of theatre seriously: From staging a performance toward staging design and innovation. In C.Clausen, D.Vinck, S.Pedersen, and J.Dorland (eds.), *Staging Collaborative Design and Innovation: An action-oriented participatory approach*. Cheltenham: Edward Elgar Publishing.

Williams, R., and Edge, D. (1996). The social shaping of technology. *Research Policy* 25(6): 865-899.

Williams, B., and Figueiredo, J. (2014). L'ingénierie hétérogène portugaise. *Revue D'anthropologie Des Connaissances*, 8(2), 279-306.

Webster, A., and Gardner, J. (2019). Aligning technology and institutional readiness: the adoption of innovation. *Technology Analysis and Strategic Management*, 1-13.

Yoshinaka, Y., and Clausen, C., and (2020, forthcoming). Navigating with people and objects – strategic concerns. In C. Clausen, D. Vinck, S. Pedersen, and J. Dorland (eds.), *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach*. Cheltenham: Edward Elgar Publishing.

8. APPENDICES (PAPERS)

Appendix A. Engineering Readiness: How the TRL Figure of Merit Coordinates Technology Development

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Abstract

This paper demonstrates the coordinating roles played by decisionmaking concepts such as Technology Readiness Level (TRL) in industrial engineering practice, where technology development is increasingly complex, involving diverse stakeholders, engineering tools and sociotechnical objects. Such distributed practices demand coordinated efforts across specialized units with diverging interests and perspectives on how development is being defined and accounted for. Nonetheless, coordinating roles of decision-making concepts in industry have largely escaped the recent attention of scholars within engineering studies and Science and Technology Studies. This paper offers an auto-ethnographic study of how the TRL figure of merit was deployed in an industrial organization. We ask how TRL is made to perform as an effective coordinating device. Following the TRL device across project meetings, we consider the three moments of a calculative device as defined by Michel Callon and Fabian Muniesa, to illuminate how TRL serves to circumscribe, configure and coordinate encounters and activity in a technology development project, as managed by the corresponding author. Contrary to linear and mechanistic understandings within management thinking, we show TRL is more than a figure of merit for measuring progress. In the hands of skilled practitioners, TRL also performs as a centralized calculating device to orchestrate distributed activities.

Keywords: Auto-ethnography; Calculative Devices; Engineering Practice; STS; Technology Readiness Levels

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INTRODUCTION

This paper addresses the coordinating roles played by decision-making concepts in industrial engineering practices, by considering how the *technology readiness level* (TRL) figure of merit[1] performatively circumscribes and configures the *temporary spaces*[2] where technology development activities are staged. Such spaces harbor multiple active elements beyond the human, including engineering practices, test procedures, prototypes, project templates and management concepts.[3] We are particularly interested in non-human elements seen to play key roles in how a temporary space is coordinated around changing scopes of action. To this end, we draw on notions of calculative devices from the early laboratory studies[4] and more recent work by Callon and Muniesa[5] on the role of calculative devices in market creation, extending these notions to engineering practice in industry. By viewing the TRL figure of merit as a calculating device, we consider the role TRL plays in circumscribing, configuring and coordinating an industrial technology development project, with a focus on how a centralized calculating device and distributed development activities are mutually shaped.

Though sprawling in scope, there is widespread and recent scholarship drawing on theory from Science and Technology Studies (STS) to describe interdependencies and interwoven relations between the social and material in engineering practice. Based on interviews and field studies of engineering projects Trevelyan points to the role of distributed expertise as a key foundation for engineering practice. Trevelyan argues that 'engineering relies on harnessing the knowledge, experience and skills carried by many people' and that engineering practice includes the rearrangement of 'components, materials, and abstract data to produce products with economic or social benefits'.[6] Accordingly, social interactions should be seen as an integral element of engineering practice and not something peripheral to a technical core. A further indication of the interrelated character of the technical and the social in engineering can be taken from ethnographic studies of engineering design activities in industrial manufacturing and a design office.[7] Drawing on actor network theory, Vinck points out the key role of objects in engineering and how 'the equipping of intermediary objects is a central concern for engineers and technicians', particularly as they move knowledge across engineering domains and boundaries of organizational responsibilities.[8] Though studies of socio-material relations including the role of objects in engineering work are rather widely reported,[9] there is only limited research on how devices such as TRL are made to play a coordinative role in the management of engineering work in technology development.[10] Furthermore, the extant literature on TRL suffers from a paucity of ethnographic studies looking at engineering and managerial practices in industry. Instead, that literature primarily theorizes from surveys and managerial opinions. As an alternative, this article investigates a specific case and contributes to shifting the mainstream theorization of TRL – towards understanding engineering and managerial practices with calculative devices. While such devices are widely used, little is documented regarding the role they are made to play and how they are used in everyday engineering. Our interest is not so much to characterize a specific role of the device but to understand what and how an engineering device performs, and the consequences of its use in practice. By investigating TRL specifically, we shed light on a key component of engineering practices, as it performs work in a non-linear cycle of development.

Though closely aligned with the work of Vinck, our auto-ethnographic approach sets this paper apart from previous studies and provides new empirical insight into how technology development is actually practiced and coordinated by those employed in industry.[11] Our case stems from a *technology development project* (TDP) led by the corresponding author.[12] We begin with a brief introduction to our empirical methods and the development space wherein our study takes place. We then review established STS notions of devices and objects and the role these play in development processes, interpolating their relevance for spaces of technology development. Later we provide a narrative spanning the development space, from its inception to the outcomes of its endeavors, intersecting with two TRL Assessment meetings and their associated preliminary and follow-up meetings along the way. Finally, we reflect upon this narrative, drawing on the notion of a calculative device and other 'material-semiotic tools, sensibilities, and methods of analysis' to show how our findings contribute to the understanding of a specific engineering practice centered around the TRL device and how such practices are organized and coordinated.[13] Specifically, we aim to illuminate the work of technology managers and engineers, and how they use concepts as devices to coordinate complex development projects in industrial settings.[14]

AN AUTO-ETHNOGRAPHIC STUDY OF TRL IN THE HANDS OF SKILLED PRACTITIONERS

The corresponding author was acting TDP Manager from the project start; planning, facilitating and executing all activities leading towards and including the TRL Assessment meetings described here. Empirical data stems from audio-recordings and a journal made by the TDP Manager. Both serve as tools for (re)considering actions, 'in the order in which they happen and in the sensible order, given that the two things are practically indissociable for human beings'.[15] *Sensible order* means the order that 'makes sense to people [. . .] linked to what they do, to the actions they carry out, and to the results and performances they obtain'.[16] The authors also recorded observations from the TRL Assessment Meetings, discussing them with the TDP Team and other stakeholders in follow-up meetings. Finally, preliminary findings were (re)considered in plenary discussions with project participants. It was within the framework of these discussions that an inkling of TRL's performing as a calculative device took form. One example stems from a discussion including project participants and the authors following the first Technology Readiness Assessment (TRA) meeting. The

Technology Director for the Work Functions Division (WF) of Danfoss Power Solutions ApS (DPS), broadly defined a *technology development project* (TDP) as:

> Where we identify and develop more or less obvious opportunities for an immature concept, or combinations of concepts, for inclusion in a product development project. [. . .] So there are a minimum of surprises and delays later, on its stringent path to market [. . .] Ideally, we predict challenges and communicate and develop solutions for these concepts before they arise in formalized agreements with customers.[17]

A few minutes later, the Technology Director coupled this endeavor to the TRL device:

> [D]iverse stakeholders used a lot of, maybe superfluous, time discussing wordings in today's assessment. But these wordings provide written consensus for the actions and resources we need.

This observation triggered a visceral response in the corresponding author, who remembered the pressures of iterating and documenting highly technical, individual statements in the fixed formats of an Excel template, as these were projected on a large screen, and eventually finalized in written 'common statements' from which specific activities could be defined and executed. The corresponding author decided to share his experience as 'assessment facilitator' with the group, using STS theory to (re)conceptualize TDP and TRL. According to the corresponding author, TDP could be viewed as a collection of spaces, where the functionality and reliability of inventions are negotiated and improved across specialized networks, that these inventions might be incorporated into new applications with minimal risk. Further, the corresponding author proposed that TRL performs key coordinative work in fulfilling this mandate, both limiting and expanding *possible* means of action as the TRL device is positioned to constitute, configure and coordinate the TDP space. Despite their unfamiliarity with STS theory, these conceptualizations seemed to resonate with the industrial participants, all of whom were engineers.

According to Vinck, engineers are particularly adept at recognizing, positioning and responding to objects that condition often conflicting intentions.[18] '[E]ngineering is above all a *work of coordination*, linked to practice-related contingencies and to the distribution of expertise among multiple actors'.[19] To illuminate the role of the TRL device in driving such work, we draw upon the sensitizing notion of *temporary space*, 'aimed at sensitizing our attention towards the configuring, political and discursive elements of distributed spaces for [. . .] innovation'.[20] Clausen and Gunn list numerous configuring elements of such spaces:[21]

> [C]ontent and meaning of the space as it is defined in the purpose and idea of the project set-up, where the participants are enrolled. [. . .] The design approaches to the staging of interactions, the methods employed, and competences of the facilitators setting up the space. [. . .] The navigation of the discourse and

> political agenda defining meaning and content of the space. [. . .] The collaborative design of intermediary objects [. . .] for staging interactions in the temporary space and the wider travel of the gained insights out of the space and into [other spaces and . . .] organisations.

In the 1970s, NASA developed Technology Readiness Level Assessments to achieve a ‘discipline-independent, programmatic figure of merit (FOM) that allows more effective assessment of, and communication regarding the maturity of new technologies’.[22]

These measures were published externally as a 7-point scale in 1989,[23] but the proliferation of TRL in the public and private sectors seems to have gained momentum from 1995, when Mankins expanded TRL to the present 9-point scale proliferating in government and industry.[24] While Mankins does not explicitly define ‘figure of merit’, his contextualization supports a widespread definition of FOM as ‘a numerical quantity based on one or more characteristics of a system or device that represents a measure of efficiency or effectiveness’.[25] Figure 1 illustrates the standard TRL-scale used by NASA, with level definitions described to the right and their six overlapping subgroups to the left.

DPS *technologies* do not encompass the comprehensive, developmental research emanating from organizations like NASA. While NASA TRL1 includes fundamental research (e.g. principles for hyperspectral imaging of hydrated salts on slopes from a spacecraft orbiting Mars), DPS development is typically associated with novel configurations of more mature elements.[26] In this case, *basic principles* were circumscribed via steering-unit patents[27] and rated according to a TRL-scale designed by and for the division.[28] Though different DPS divisions employ customized scales for Technology Readiness Assessments, the TRA process and its related elements are well-structured in a ‘Global Standard’ and an Excel template through which TRA and participants are documented. Presupposed outputs of this process include: ‘Identified critical technology elements to be assessed’, ‘Collected evidence of maturity’, and ‘Assigned TRLs and reviews of TRA Report content’. [29] These standardized results are meant to feed directly into development per a ‘Corporate Standard’ describing the ‘milestones’ and ‘critical integration points’ that comprise the Product Development Project (PDP) process into which TDP are intended to flow.[30] This PDP process is dimensioned using decision-making *gates* á la Cooper,[31] where ‘Milestone and Project Deliverables’ and ‘Milestone Deliverable Definitions’ are described in another corporate standard that connects achieved *readiness levels* to the completion of early milestones.[32]

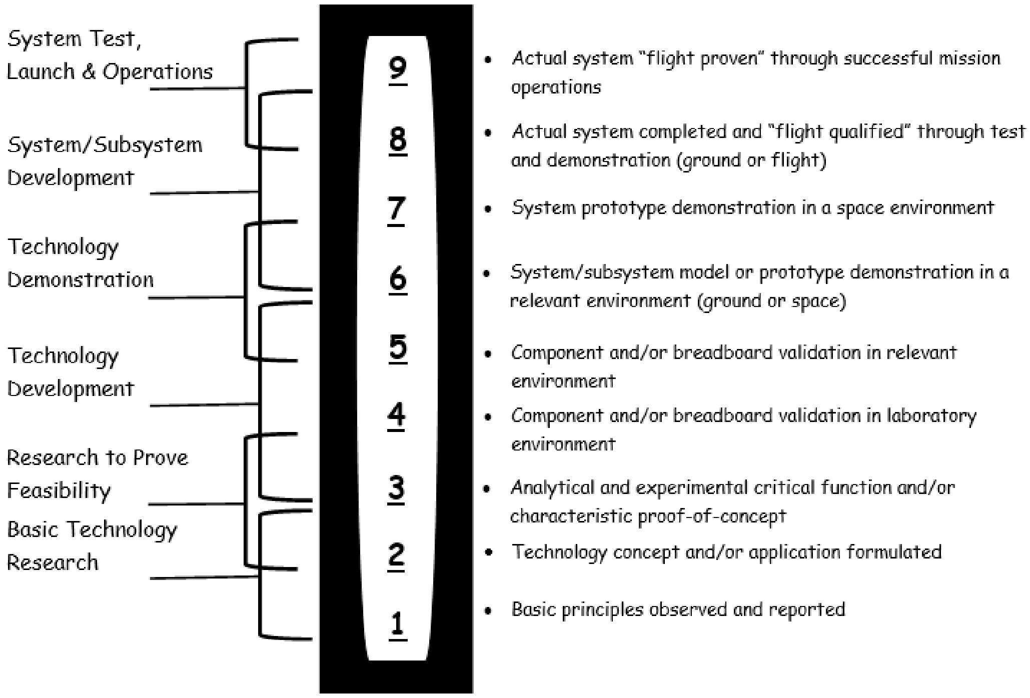

Figure 1: Authors' rendition of NASA Technology Readiness Level definitions cf. Mankins. WF Division employs a similar 9-point scale, with different definitions. Note: Mankins, "Technology Readiness and Risk Assessments," 1211.

Critically considered, the company TRL is an idealized sum of many parts, all of which coalesce around a 9-point scale, dimensioned towards a mechanistic, supposedly rational and autonomous linear model of innovation and closely tied to the allocation of project resources. Despite significant historical and policy literature arguing against assumptions of science driving engineering progress, a large portion of the TRL literature draws on a widespread assumption that basic science is the root of linear progress at higher levels of innovation.[33] As a tool to ascertain progress at 'key points in the life cycle of the program',[34] the ways by which TRL is meant to complement sequential process-models have been readily described (e.g. 'New Product Development', 'Risk Assessment', and 'Supplier Qualification').[35] These descriptions reflect TRL's assumed efficiency in determining positions on a linear trajectory, as a system for measuring *stages* of development, where the TRL scale and placement of its denominations behave as expressions of progress. Still, the mechanisms by which non-linear development processes are stabilized (through coordinative action and the construction of sociotechnical networks defining the technology) are out of focus, if not wholly unconsidered.

Though wanting in TRL literature, the coordinating contribution of the TRL device is widely acknowledged at DPS. According to an experienced Project Manager (who is tasked with implementing supposedly mature technologies into *product development projects*), this coordinating work is certainly on par with its ability to denote progress.

> I need to know what you did to get to three or four and what I need to do to get to four or five [. . .] It's equally important that I know what I'm walking into. So, I can approach you when we start the product development project, and ask, "Hey, what did you do, with this specifically, to get to this point in the project?" It's that sort of information I'll need to know. The numbers are secondary. I will likely inquire more about the state of a TRL2, than I will a TRL4. But really, that's how I will use this score.

The Project Manager's clarity, over how TRL performs the coordination of action in non-linear cycles of development, stands in stark contrast to the extant TRL literature. This supports Vinck's observation that outside the field of design, very little is understood of engineering practice in industrial organizations; much of what engineers do and how they do it remains a mystery.[36]

THE ROLE OF DEVICES AND OBJECTS IN DEVELOPMENT PROCESSES

STS offers a variety of notions concerning the performance of objects and devices in development processes. Here we briefly consider devices of interessement, boundary objects, intermediary objects, (re)writing devices and calculative devices as sensitizing concepts – 'interpretive devices serving as a starting point for a qualitative study'.[37] Our review of objects and devices starts from how such concepts perform in connecting exigencies of the technical and social in engineering practices, so that their roles in coordinative efforts might be clarified.

According to Callon, *interessement* of actors requires 'devices which can be placed between them and all other entities who want to define their identities otherwise'. This is a notion of a device in a one-to-many relation, an entity imposing and stabilizing other entities. Devices of interessement are thus integral to 'actions by which an entity [. . .] attempts to impose and stabilize the identity of the other actors it defines through its problematization'.[38] As such, *devices* are a principle element of Actor-network Theory, which addresses sociotechnical constructions as networks of association that follow translations between heterogeneous entities.[39] Considering similar problems of translation, Star and Griesemer took issue with the way devices of interessement and obligatory passage points 'can be seen as a kind of "funneling" – reframing or mediating the concerns of several actors into a narrower passage point' favoring a single point of view.[40] Consequently, Star and Griesemer proposed an alternative, 'many-to-many mapping, where several [OPP] are negotiated with several kinds of allies'.[41] This notion of devices, in a many-to-many relation, stems from a pragmatist view of social worlds as 'groups of activity having neither a clear border nor a formal and stable organization [. . .] built up through the relation between social interactions generated by the primary activity and a suitable definition of reality'.[42] To accommodate these social worlds, Star and Griesemer's analytical framework includes two sensitizing concepts: *methods standardization* and *boundary objects*. Methods standardization takes root in 'elaborate collection and curation guidelines [that] established a management system in which diverse allies could participate concurrently'. Boundary objects are, in contrast, 'both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites'.[43] By definition, the boundary object notion is suitable for analyses of translations 'intersecting social worlds'. Alternatively, Vinck's notion of the *intermediary object* is suitable for analyses independent of these intersections. Being 'open to interpretation in terms of the mechanisms at work', the intermediary object's weaker conceptualization makes it applicable for a broad variety

of situations.[44] Though both notions 'account for the materiality of things that actors produce and use in a given situation',[45] boundary objects must maintain an aptly common structure to make them recognizable across multiple worlds.[46] In contrast, an intermediate object may transform the intentions, associated knowledge, identities, and power relations governing its design – even if the intention is to maintain a common structure (as this is the case with a boundary object). [47]

As we have seen above, the notions of interessement devices, boundary objects, and intermediary objects vary in the way they attend to the configuration of network formation. Interessement devices assume a center, a key actor from where the identities of the other actors' identities are subject to negotiation. Contrariwise, boundary objects, 'inhabit multiple worlds simultaneously', allowing for multiple distributed identities and a many-to-many negotiation.[48] In comparison, intermediary objects can be viewed as *objects on the move*, carrying knowledge, identities, values, constraints, and roles from network to network as they shape, translate, transform, structure and organize.

To address this complexity, Vinck, Jeantet, and Laureillard separate intermediaries into two different roles: *commissioning objects*, which passively serve 'rational and appropriate means of pursuing specific objectives', and *mediating objects* that include both 'actions and mediations' with 'active and interactive roles'.[49] These categories are extensions of 'Latour's voluntarily materialistic point of view [. . .] that there is a proliferation of [hybrid] intermediary objects' commuting between different roles.[50]

Advancing the notion of intermediary objects, Clausen and Gunn consider intermediary objects as networks including human and non-human elements. To address 'how intermediaries are staged within temporary spaces and how they perform in practice', they trace relations between the performance and configuration of intermediaries, illuminating how 'knowledge [is] generated, packaged, transported and unpacked across [. . .] sociotechnical spaces'.[51] This resonates with Vinck's problematization, that 'the content and consistency of scientific work depends on elements which researchers articulate, elements whose origin and trajectory influence the work in progress'.[52]

Callon posits *(re)writing devices* as 'important in establishing and transforming systems of collective action because they work by a method of *successive adjustment*', where: 'They also make possible the progressive expression of demands that are partially undetermined and the definition of actions needed to respond to such demands'.[53] (Re)writing devices thus draw our attention to the unfinished nature and definition of technology and help us investigate how technology is continuously being redefined as it is being developed – as expressions of expected criteria of performance are revised in real-time. (Re)writing devices also possess a *centralized function*, endowing agents 'with the ability to calculate. They render decisions calculable and locate the maximum power to calculate a single point in the managing director's office'.[54] Advancing this premise, Callon and Muniesa have addressed what *calculation* does – as inherent to their own *calculative device* notion. 'Calculating starts by establishing distinctions between things or states of the world', so that *courses of action* associated with these things or states can be estimated and their consequences considered.[55]

This broad definition of calculation builds on Cochoy's 'qualculation', a notion of calculation that includes judgement and focuses on 'arrangements that allow calculation (either quantitative or process, qualitative) and those that make it impossible'.[56] Formulating a general definition of calculation as a three-step process, Callon and Muniesa developed their calculative device notion to address processes of economic network-stabilization, with 'emphasis on material movement – also found in the "centre of calculation" notion developed by Bruno Latour'.[57] Within this *centre* economic calculations are made possible as goods are 'calculated by calculative agencies whose encounters are organized and stabilized'.[58] While our consideration of TRL as a calculative device falls outside the scope of calculations for Callon and Muniesa's economic markets, we propose acts of configuration as the real subject of their work. Callon and Muniesa utilize economics to speak with economists, but more importantly, they build upon *centers of calculation* to describe how a calculative device performs configurative tasks in 'a cycle of accumulation'.[59] In our case the cycle of accumulation refers to the stabilization of technological networks taking place in the movement from an idea of a technological solution to a well-defined technology, where the performance of the technology must be demonstrated for, and accepted by, Senior Management before entering into a *product development project*. We thereby suggest, that the calculative device sensitizes the coordinative work performed by TRL from a (management) center in the configuration of sociotechnical networks – through the translation of diverse knowledge concerning user and customer demands, and knowledge derived from simulation of the performance of prototypes. Within this process, the working of technology is demonstrated as different types of certainty are being constructed, while a level of scaling of the technology is being accomplished. In this sense the concepts of (re)writing and calculating devices clearly depart from the notions of both intermediary objects and boundary objects, by considering the perspective of centralized agency in line with the classical work of Callon discussed above.

We thereby find it meaningful to extend Callon and Muniesa's notion to include a process of *technologic* network-stabilization, encompassing the same three calculative moments: circumscribing agencies; (2) organizing encounters; (3) and establishing conventions. Introducing the calculative device notion into our analyses is intended to sensitize readers to the cycle of accumulation to which the TRL device is directed – as demonstrated in the following empirical narrative.

A CASE OF NETWORK STABILIZATION ACROSS TEMPORARY SPACES OF TECHNOLOGY DEVELOPMENT

Our technology development project (TDP) began in 2015. A part-time project group in WF placed second in the Danfoss Man on the Moon Competition (MotM), submitting two patent applications for a novel steering technology that could make full hydraulic steering (see Figure 2) safe and comfortable at speeds over 50 km/h.[60] Six months later, WF Senior Management selected this steering technology for further development and a preliminary TDP Team was tasked with defining a course of action. Over the following months, additional resources were secured, and a five-member Core Team was constituted. This team included a TDP Manager, a Simulation & System Specialist, a Mechanical Hardware Specialist, a Simulation & Design Specialist (from the MotM group), and a Senior Design Specialist. The Team's additional resources included a mandate to purchase and utilize a GPS Motion Package and Steering Robot[61] to mature the technology through internal variations of Automotive Industry standards at the company test-track.[62] When the events that follow here began, the TDP Team had submitted eight additional patent applications, developed and tested three prototypes, and devised numerous test-specifications, equation-based dimensioning tools, dynamic simulation models and methods of analysis – all purposed with establishing the validity of the steering technology's functionality and reliability in off-highway vehicles for the construction and agricultural markets in which WF operates.

The following narrative illustrates aspects of these complexities and demonstrates the unruliness of the process in which TRL performed. Following the device from meeting to meeting, it is apparent that Callon and Muniesa's calculative moments are neither self-occurring nor linearly connected. All three moments are simultaneously in play as the TRL device mobilizes (and is mobilized by) intermediary objects engendering new problematizations. As we intend to demonstrate, these calculative moments were part and parcel of how the TRL device, notions of functionality and reliability, and the technology itself were renegotiated at every meeting, and of how the technology was later stabilized within an overarching center of calculation – where undisputed notions of functionality and reliability could be established and exploited.

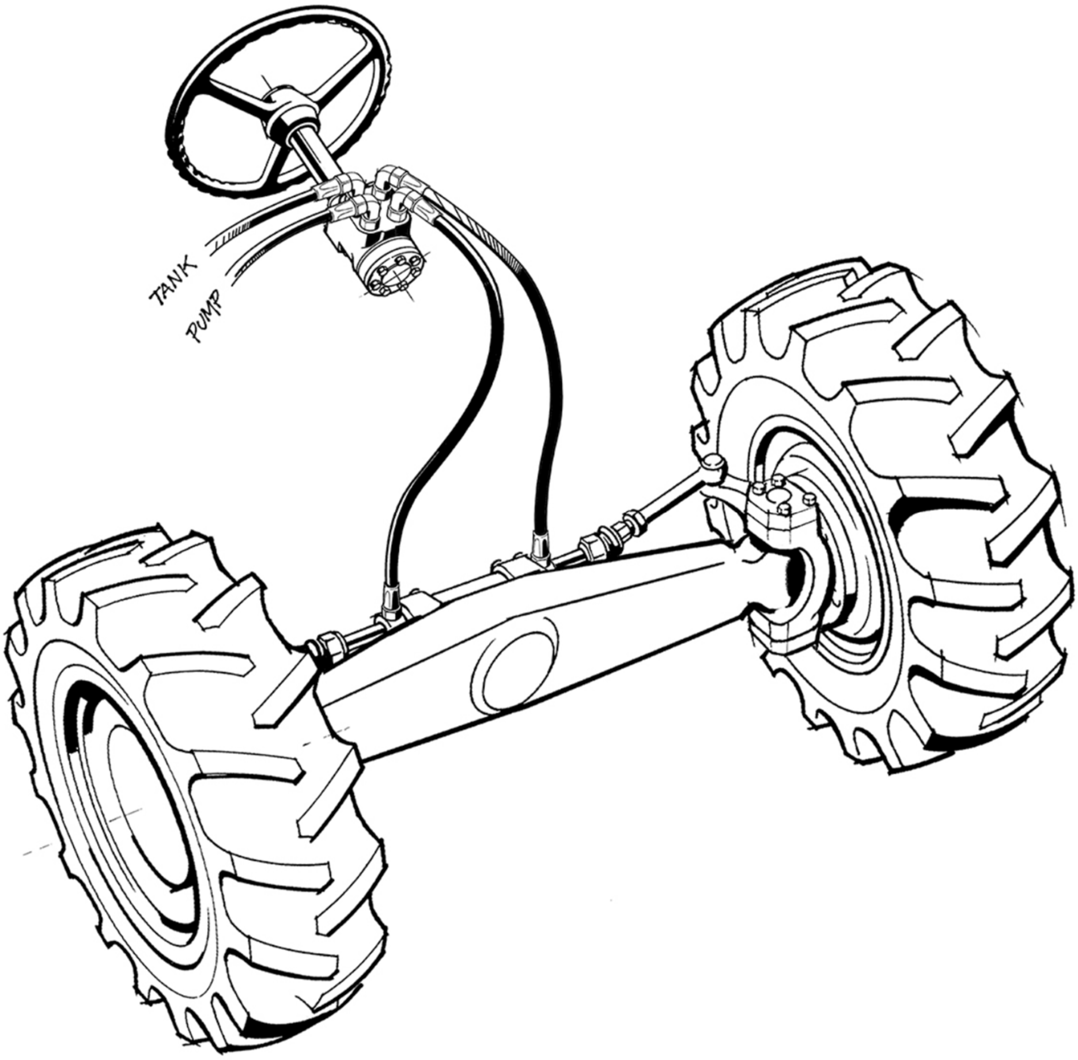

Figure 4: A full hydraulic steering system comprising 'hydraulic pipes and hoses between a steering-unit and steering cylinder[s]', where the steering-unit meters oil to the cylinder(s) through the steering-wheel interface. Note: Danfoss A/S, Steering General, S

Initially, questions of functionality and reliability were limited to negotiations within the TDP Team, occasionally extending to include Senior Management (Presidents, Vice-presidents, Directors and Senior Managers) regarding project resources and deliverables. The frequency, scope, and complexity of these negotiations grew considerably after the WF Sales Team invited two large OEMs (*original equipment manufacturers*) to test-drive prototypes in their own vehicles at the DPS test-track. As news of the successful demonstrations spread, the DPS President and Vice-presidents requested a test-drive of their own.[63] A few days later, the Company's Chairman of the Board and CEO were also at the test-track to benchmark the new technology. Following these demonstrations, focus on commercialization was sharpened and the deadline for delivering a ‘reliable and functional steering technology’ to a *product development project* (PDP) was moved forward. To continually gauge the readiness of this transition and react accordingly, a series of TRL Assessment meetings were planned. Henceforth, both the project and the TDP Team would be appraised according to how notions of functionality and reliability transitioned through the readiness levels of the TRL device. Consequently, the TDP Team needed to establish *which* notions of functionality and reliability would be included in the TRL device, *how* these notions would be defined, and *whose* expertise and influence would be included in assessments.

The day before the first TRL Assessment Meeting, the TDP Manager (TPM) met with the TDP Mechanical Hardware Specialist (MHS) to align their intentions. The meeting took place in a large room dedicated to the project. The room included three whiteboards filled with notes, design sketches, hand-drawn Gantt charts and magnets holding CAD drawings, test-reports and photographs of prototype tests. TPM and MHS sat at a large table littered with steering-unit components and printed copies of ISO test standards. The TDP Team had roughly filled in sections of the TRA Template a few days earlier, without adding scores (see Figure 3). These sections included the names and titles of TRA participants ‘The description and scope of the technology’, ‘Purpose/Requirements of the New Technology’, ‘Composites of the New Technology’, and ‘Purpose/Requirements of the Composites’. Where applicable, the TDP Team had included SDP-reports supporting specific evaluations.[64] While not all SDP-reports were started (and some would be made irrelevant before they were complete), they provided a basis from which the team could define and execute activities for proving specific aspects of functionality and reliability. The template was projected onto a screen that was pulled down over the largest of the three whiteboards. Both TPM and MHS had printed copies of the TRL-scale to which they would sometimes refer or read aloud in support of an argument. The meeting agenda was ‘to define the steering technology’s functionality and describe how these definitions were supported’, so they could be presented for participant’s in the next day’s assessment. TPM and MHS would also discuss unsettling results from in-situ tractor tests with the newest prototype. Though laboratory tests and component simulations had pointed towards better performance, the prototype showed system instability which the team could not explain, according to a new test-procedure which the TDP Team had derived from ISO standards designed for the automobile industry. Though TRL does not make explicit demands for understanding, the TDP Team could not define actions for moving from TRL4 (validation in a *laboratory* environment) to TRL5 (validation in a *relevant* environment) before addressing this instability.

Purpose/Requirements of the New Technology	TRL	Comments
Zero-deadband steering		Zero (0) deadband in a steering system, [redacted] (SDP0248).
Self-alignment		Subjective tests in vehicle are completed (SDP0247). A possible objective vehicle test is also formulated in the report. Q-lab (SDP0213; SDP0223)
Emergency steering		Demand restricted to SU under [redacted]. Three different principles have been tested in Q-lab using external valves (SDP0240).
Energy consumption ≤ [redacted]		Measurements made in Q-lab and in vehicle (SDP0250).
Functionality with/in [redacted]		Comparitive measurements made on vehicle acording to [redacted] tests from 2016 (SDP0255).
Manufacturability		Prototypes produced in DPS processes verified in Q-lab and vehicle (SDP0250; SDP251; SDP0252; SDP0253). New [redacted]-equipment is needed.
TRL result :	**0**	

Composites of the New Technology	TRL	Comments
Spool-sleeve set		Designs of new spool-sleeve sets verified in Q-lab and in vehicle (SDP0250; SDP251; SDP0252). CAD models exist (SDP0250).
Housing [redacted] w/o em. steering)		Design of new [redacted] housings verified in Q-lab and in vehicle (SDP0253; SDP0251; SDP0252). CAD model exists (SDP0253).
Housing [redacted] with em. steering)		Principle has been tested (SDP0240. CAD model exists (SDP240).
Housing ([redacted] w/o em.steering)		Principle has been tested (SDP240).
Valve [redacted]		Component is released (part number XXXXX). Tested as emergency steering principle in Q-lab, as an external valve (MDP0240).
Gear-set		No changes made to released gear-sets. Diverse displacements verified in Q-lab and in vehicle (SDP251; SDP0252).
[redacted]		Component is released (part number XXXXX). All verification tests made with [redacted] (SDP251; SDP0252).
TRL result :	**0**	

Figure 3: Excerpt from the WF Division TRL Template, with the TDP Team's preliminary (and incomplete) evaluation of the novel steering technology, according to the purpose/requirements of the technology and its composites.

The meeting started with TPM and MHS outlining the TRL device and how they expected it to perform. Though TPM and MHS knew their conclusions would be renegotiated in the upcoming meeting, they saw a clear relation between delimiting the TRL space and their ability to accommodate future challenges (the WF Technology Director would support this hypothesis in another statement at a later meeting). In line with Callon and Muniesa, they needed to establish preliminary 'rules or conventions' and to set the order in which their problematizations could be treated and made *accountable* (i.e. answerable and explicable).[65] TPM and MHS needed to define their center of calculation.

> TPM: I see TRL as a tool to help prioritize the tasks needed to mature the technology. To foster a common understanding of its progress, so when it's placed into a PDP project the team can achieve, or more easily achieve, their milestones. This is an extension of the PDP process as a series of milestones. TRL helps assess if the technology is ready to enter into conversations or agreements that comply with specific milestones, so TDP work can make compliance possible.
>
> MHS: It's true. [. . .] Within the TRL meetings we must somehow reach a common understanding of how we interpret the development activities. Assessments must contribute to finding the right level, so that we all agree on what an activity means in order that it can be pursued.

After establishing basic conventions governing their interpretation of the TRL space, TPM and MHS discussed the Team's definitions of *steering-characteristics,* as the sum of interrelated, key-knowledge objects that would make it possible to translate notions of *functionality and reliability* into something measurable. These knowledge objects included abstract concepts like *self-alignment*, which describes how a vehicle's steering-wheel returns to its start position when released after a turn, and *zero-deadband*, a measure of the hydraulic slip in a steering-wheel, and how many degrees it should be turned before the steering column is engaged (ideally zero). Measuring such abstractions required more tangible items, like the new GPS Motion Package and Steering Robot which they were still learning to utilize.

> TPM: It's back to what you said, a common understanding. How do we define things? What do we mean by steering-characteristics? What do we mean by self-alignment or zero-deadband, and what does reliable mean to us? [. . .] How do you think the TDP Team is aligned in the definitions that we'll share in the assessment tomorrow? Can we distinguish between the concepts in our current product's measured functionality? Can we make zero-deadband without self-alignment?

As they considered zero-deadband and self-alignment, TPM and MHS realized that the TRL Template needed to do more than just establish connections between conceptualizations of functionality and reliability. They also needed to connect these conceptualizations with the goals of the Assessment Group (the primary *calculative agency* for whom their TRL preparations where directed).[66] Hitherto, the prevailing notion of *reaction* (the ability of a steering-unit to hydraulically reposition itself when the steering-wheel is released) had sufficiently *circumscribed* a generalized, widely understood phenomenon (i.e. critical elements comprising the complex network upon which the reaction conceptualization relied were identified and made accountable). However, introducing the new GPS Motion Package, Steering Robot, and ISO standards into the development space had repositioned the TDP Team's focus. While this helped them to identify and develop *self-alignment* (a superior notion for conceptualizing the functionality and reliability of prototypes), it necessitated reflections around a new circumscription – by which their new knowledge (engendered through experiments with new equipment and standards) might be negotiated and acted upon. Though TPM and MHS planned to include self-alignment in discussions at the TRA meetings, few outside of their team understood the relation between the division's notion of reaction and the new concept of self-alignment. MHS had experienced this disconnect firsthand, in previous demonstrations and in workshops with colleagues on measuring the new technology's performance. While reaction and non-reaction were *binary* concepts for deadband steering, self-alignment was intended to conceptualize *specificities* of reaction in zero-deadband steering – specificities which the TDP Team still needed to define and validate in cooperation with the division's engineers and salespeople.

> MHS: We are not at the bottom of this. There are different perceptions. Not everyone understands the difference between reaction and self-alignment. It's important to keep the two separated. They are two different features, but those who separate them are not entirely clear on the differences. It's our responsibility to present self-alignment with its inherent qualities and the novelty it offers. We

> must sell that because they [the Assessment Group] don't really understand its value.

Moving forward, TPM and MHS recognized that incorporating the notion of self-alignment into the TRL Assessment space was confounded by another factor. Though reaction and self-alignment were both system dependent variables, the TDP Team did not fully understand how the system correlated to the newest prototype's instability. This led TPM and MHS to reconsider the TRL Template itself. They saw limitations in how the template's *conventions* set the order in which the system dependent variables could be treated and accounted for.

> TPM: [standing and pointing to the TRL Template projection] Considering the unexpected instability we've seen in the newest prototype [. . .] Is there a way, with the individual boxes in the Template, that I can write system compatibility? Where I can address system-understanding in this Template? Can system-understanding be analyzed in this Template along with the steering technology?

> MHS: Good question! No, and it's really an Achilles heel, because the steering-unit is integrated into a complete system. Traditionally, Engineering considers the steering-unit as an isolated device. And then everything else is just the black-box where it's placed. [. . .] But it's not just the steering-unit, we are also up against priority-valves, hose lengths, etc. Though the new Automotive equipment helps, we are not particularly strong in system correlations. [. . .] We must be open with the Assessment Group about this.

Interestingly, the principle outcomes of this preparation meeting were related to *how* steering characteristics could be conceptualized. Though TRL levels are themselves expressions of material progress, the methods by which steering-characteristics were or could be materially manifested, measured and evaluated were only briefly addressed in their 60-minute interaction with the TRL Template. Instead of utilizing the TRL device to document the steering technology's present *stage* of technology readiness, TPM and MHS focused on how notions of functionality could be *staged* within the TDP space.

A similar focus was apparent in the TRL Assessment meeting the following day. Three-quarters of the meeting was spent negotiating the 'Description and Scope of the Technology' and (re)writing it into the TRL Template in accordance with (re)negotiated steering-characteristics. While TRL point scores were only given after stable definitions of conceptualizations were achieved in plenum (as these were projected on a screen and revised in the TRL template by TPM in real-time), discussions of specific TRL levels often destabilized previously accepted definitions, fostering new negotiations and revisions of already completed scores. For example, when results of benchmark procedures for provoking steering-unit instability in stationary tractors were discussed and deemed 'ambiguous for the new technology' preliminary demands for new *In-situ Test Specifications* had to be negotiated. In turn, these demands fostered new definitions of 'relevant environments', expanding the scope of tests necessary to achieve TRL5. Consequently, the Assessment Group was unable to accommodate widespread concerns with the new prototype's functional instability, nor define how to address them. In the final minutes of the meeting the following text was included under the section of the TRL Template called 'Purpose and Requirements of the Technology'. The writing and rewriting process by which this statement was composed (in a plenary session including 11 people from different functions) is an excellent example of the workings of the TRL device. The Excel Template was visible to all stakeholders, projected on a large screen at the front of the meeting room. While participants spoke, the TDP Manager erased, added, or appended text directly into the template, selecting recurring points from concurrent conversations. As sentences took form, the Assessment Group would suggest changes or express (dis)agreement in real-time (e.g. 'No', 'Precisely', or 'The grinding process is not a relevant parameter'). Occasionally, TPM asked for clarification or elaboration of a frequent or passionate statement. Initially, everyone seemed to be speaking at once, rarely to TPM, sometimes to a colleague and often to the entire group – gesticulating towards the screen or a colleague across the table. As sentences on the screen gained coherence, the number of parallel conversations decreased and there were fewer interruptions. The meeting adjourned when TPM read the following statement out loud (twice), without protests or recommendations to its composition, adding 'So we are married to this now. Everyone's good?'

> We have experienced, through design changes that were expected to make improvements, setbacks which lead us to believe we do not completely understand the parameters governing self-alignment. It is also unclear how to manipulate these parameters. Analytical and experimental activities need to be updated according to TRL 3.

Following the Assessment Meeting, the TDP Team met to discuss the results. Referring to the above text, the TDP Simulation & System Specialist (SSS) proposed that models and simulations ought to be better connected to the *readiness scale* of the TRL Template. In the following citation, SSS moves beyond notions of how the TRL Template's levels can be interpreted and suggests redefining the levels themselves. This was a radical proposal, potentially changing the functionality and reliability of the Template itself. Instead of a static, broadly applicable system of measure of progressive *stages*, SSS sought to incorporate level-specific, predictive demands for *staging* transitions between levels.

> SSS: It should be about readiness. There is a need for a connection between how well we are in control of this technology and if so, can we justify why it works? We may have just been lucky with a mock-up that works, as opposed to making a theory of how it works and then via verification, proving the theory. I miss a parallel between an early concept, there is one called mock-ups [in TRL 4], and the analyses.[67] They can be static models, simulation models [TRL 3].[68] But they should meet in the fifth level before you can move on to the sixth. Have you

> passed it? When I read the definitions cynically, they don't make requirements for how I meet the mock-up at level five. I would like to know that along the way. Before you start the mock-up, you should commit to a simulation, either a dynamic or static model. In each case, you should know what calculations are necessary for working in parallel with mock-up development. Then, when you reach TRL 5, activities should meet in the test conditions and you should be able to verify the model in the same relevant test conditions.[69]

The implications of the proposal were dizzying. Instead of a static table of demands for progressing between stages, levels could incorporate *ad hoc* activities unique to each assessment. Though theoretically advantageous, it seemed unwieldly in practice. Who would approve dynamic levels that could change across projects? And how could these be broadly communicated to Senior Management as generic results? It was clear to the TDP Manager (TPM) that the scale must remain static. TPM explained his concerns and rejected the proposal.

Two weeks later, TPM had reconsidered. Tensions between how TRL was employed as a linear measure of efficacy for Senior Management and how TRL was utilized in the TDP space to 'stage' (constitute, configure and transform) non-linear processes of development by which efficacy is achieved were obvious.[70] Perhaps a balance could be struck, between a generalized scale and dialogues on 'matters of concern?'[71] The day before the second TRL Assessment Meeting, TPM met with SSS to problematize the TRL definitions with which SSS had taken issue. Interestingly, their problematizations were not limited to TRL. Definitions of what is needed for good technological development and good engineering practice were also at play. So was engineering identity: a good engineer should be able to explain *why* things are functioning and not only *prove* that they do. TPM and SSS were not just negotiating TRL, but also the role of knowledge. SSS was also defending the extent to which his specific type of expertise should be included.

> SSS: One problem in the template, is that you don't need to prove you have the background knowledge to explain what is happening with the technology. There are a lot of practical actions to show something works on a vehicle. But it only demands success in one situation. For the most part, you build your theory on that situation. It is missing parallel actions to explain why something works. Either with the help of a model or calculations. Whether static or dynamic, is not so important, they just need to prove the functionality.
>
> TPM: Yes. It's something we fight with later. We approve it based on some experiments or some tests. But there is nothing in TRL that forces us towards a deeper understanding of phenomena?

> SSS: Right! You may have a good idea, and the first prototype works. You think you're in control of it all. But maybe it's due to a limited number of usage scenarios? Reviewing past project challenges, with instability and such, I think defining a dynamic model early and testing to validate the model would foster a better understanding of what's happening.

> TPM: Okay [sigh]. How should this be formulated? We probably can't officially change the scale. It's a WF standard that needs to be approved higher up. How will the participants accept that risk?

SSS and TPM settled upon formulations for TRL 3[72] and TRL 5[73] which were meant to stimulate discussions on matters of concern in a generalizable readiness scale. They presented the new and old levels (printed on each side of an A4 sheet of paper) in the TRA meeting the following day, informing participants that the definitions were experimental and that scores were not necessarily valid for future DPS milestones. Surprisingly, and despite 'potential for lost work', participants agreed to use the new definitions and reconsider scores from the previous assessment. Interestingly, this resulted in multiple TRL4 scores from the previous assessment being re-evaluated to TRL3. This observation not only challenges widespread assumptions of linear efficacy, it shows that switching focus from one-time contextual performance to multi-contextual understandings can impede technological development – per *de rigueur* assumptions of progression between TRL levels.

While re-addressing instability issues according to the new scale, the TDP Manager (TPM) framed work to improve energy consumption as a failed activity. The Mechanical Hardware Specialist (MHS) disagreed and was supported by the Product Application Engineering Manager (AEM). An excerpt from their dialogue shows how a simple attempt to frame progress as non-linear or stagnant performed to re-frame the dynamics of the TRA meeting.

> TPM [speaking while typing]: TRL 3. Energy-consumption is too high, on measurements made in the lab and vehicles.

> MHS: No, it isn't. For the newest prototype is down to one and a half liters per minute in neutral.

> TPM: Yes. But. The crap doesn't work.

> [laughter]

> MHS: But that's not why. This is due to something else. The bad characteristics don't come from reduced flow. None of them are attributed to flow in neutral. We've shown energy consumption can be lowered. We will certainly reduce consumption. I'm not concerned.

> TPM: Can. Maybe. We don't know. All our models and assumptions said it should be better with lower consumption. But it isn't. Here's what I've written in the Template: Measurements are made in the lab and vehicle, then a report number. The first prototype didn't meet the energy demand. The second prototype met the energy demand but does not function.
>
> MHS: Oh! No! I don't know about that!
>
> AEM: It's a hard statement [laughing]. It functions? With reduced performance and instability?

This opened a technical discussion around the merits of re-positioned and re-dimensioned orifices in the prototype's spool-sleeve set. While it was possible to observe the *probable effects* of these orifices (via precisely measured inputs and outputs), behavior at the intersections of these orifices was *immeasurable*. Further, the mathematical models necessary for *calculating* behavior were either underdeveloped or nonexistent. Over the next 10 min, different opinions on the root-cause of the instability and its potential effects on customers flourished within the group. Opinions were often stated simultaneously in subgroups of two or three people as hydraulic-diagrams and components were quickly sketched and passed around the table. The controversy was finally closed when the PDP Manager (who was responsible for implementing the technology into a *product development project* later), asked how these necessary and un(der)developed mathematical models 'tied into the revised scale definitions'. The TDP Manager proposed that new models for simulating functionality (including *energy consumption* and *instability*) in static and dynamic systems could be developed as part and parcel of TRL 3 (where 'analytical and experimental activities' were defined). While the Assessment Group agreed on this course of action, it required additional resources for which they presently had no mandate: an extra *Simulation Specialist*, significant *Laboratory Investments* to validate new simulations, and a *GPS Motion Pack & Steering Robot Specialist* to help with in-situ vehicle tests.

In the following weeks, the TDP Manager leveraged the new TRL definitions to mobilize these resources. Laboratory Investments were successfully approved as aligning with 'more demanding TRL definitions' which would accelerate the accumulation of knowledge they needed to achieve TRL5. Approvals, in turn, solidified Senior Management's acceptance of the new scale, and the new demands were included in a successful bid to expand the TDP Team with the Specialists found wanting in the TRL Assessment. Models for simulating functionality in static and dynamic systems were then constructed and incorporated in an iterative design process. This process included new *Specifications for Model Validation* using the upgraded equipment, where the design of both equipment and specifications were negotiated with and around the Laboratory Technicians responsible for the tests (see Figure 4). The sum of these actions culminated in a stable, energy-efficient prototype that was proven in tractors at the test-track using new *In-situ Test Specifications* (co-created by the new GPS Motion Pack & Steering Robot Specialist and Simulation Specialists). The prototype was both the subject of and incitement for a third Assessment Meeting.

Figure 4: The TDP Simulation & System Specialist negotiating the new test specifications and possible scope of test-rig upgrades with Laboratory Technicians and the Laboratory Manager – with the aim that future simulations and experiments might coalesce around mandates established in the second TRA meeting.

A CALCULATIVE DEVICE FOR HETEROGENEOUSLY ENGINEERING *READINESS*

In his groundbreaking chapter, Law considers Portugal's historic domination of the spice trade as a process of *heterogeneous engineering*, made possible by an *emergent phenomenon* (the galley: a conglomerate entity possessing attributes not shared by its individual components).[74] Here we discuss TRL from a similar perspective, as 'a family of methods for associating and channeling other entities and forces, both human and nonhuman'.[75] In short summary, our narrative describes how both device and technology were (de)stabilized as they transitioned through (re)negotiated definitions of *readiness*.

Though the TRL device served the TDP Manager in coordinating and configuring the heterogenous actors and objects constituting the TDP space, the device was also reconfigured by other actors (e.g. the TDP Simulation & System Specialist), who successfully *(re)staged* the device to more readily achieve specific *stages* of technology readiness. As it was deployed by the TDP Manager in early interactions with the TDP Team, TRL served as both a constituting element for technological progression (*mandate*) and a configuring instrument for the inclusion of objects and actors. Later, the device helped to align intentions and common points of reference, where it was also influential in delimiting and refining the conceptualizations of functionality and reliability developed for and within the first Assessment Meeting. Though the TRL device was itself renegotiated and transformed in every TRL Assessment, it still contributed to stage resources and actions which allowed the technology to transition through a process of stabilization. These aspects fall afar of the device's performativity as described in appurtenant literature, which focused on TRL as a *figure of merit* for evaluating stages of technology progression with a view that the effects of immature technologies might be quantified with mitigated risk.

Drawing upon ANT's material-semiotic sensibilities and methods of analysis we intend to impart new aspects of the function for which TRL was constructed (and in our case, re-constructed) as a figure of merit. To further illuminate these aspects, we begin our narrative by reflecting on the three moments of a calculative device and how the TRL device was employed as a provoking dialogic instrument.

CIRCUMSCRIBING CALCULATIVE AGENCIES

In this industrial case of technologic network-stabilization, *circumscription* occurred in a process of exclusion and inclusion, where conceptualizations, test specifications, prototypes, methods of analysis, specialized equipment and reports were repeatedly combined and separated, at the test-track and in the laboratory. Considering a process of economic network-stabilization, Callon and Muniesa identify this process as the first task of a calculative device: 'to circumscribe the group of calculative agencies that are to be met, by making them identifiable and enumerable'.[76] Though we also witnessed 'a finite number of entities', identified and made enumerable to and for specific problematizations in a similar process of circumscription, this was not the first task to which the TRL device was directed (more on this below).[77] Further, circumscriptions thought complete were reconsidered in every new interaction with the TRL device, where actors seemed to shuttle between each of the three calculative moments when negotiating any of them singularly. In preparation for the first TRL Assessment Meeting the TDP Manager and Mechanical Hardware Specialist introduced the first calculative moment into the TDP space, delimiting conceptualizations of steering-characteristics and making them enumerable. Yet in circumscribing these conceptualizations, they also mobilized the second moment of a calculative device: identifying encounters between calculative agencies. In circumscribing conceptualizations of reaction and self-alignment (as differing system-dependent variables) they engendered new deliberations on how these conceptualizations could be qualified and later incorporated into the TRL Template. (Dis)associations between *reaction* and *self-alignment* were needed before either could be made enumerable. Only then could these conceptualizations be 'subjected to manipulations and transformations' and compared across systems as different, albeit similar, functionalities.[78]

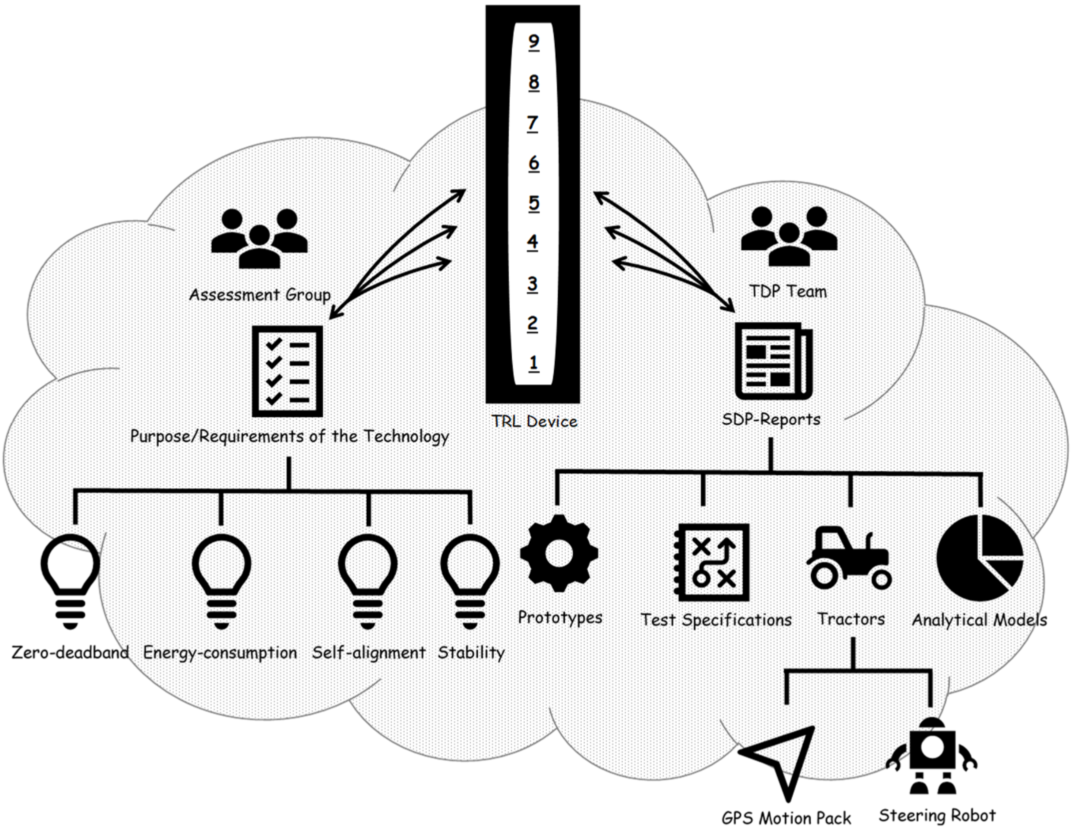

Figure 5: Organized encounters between the TRL device, actors and objects in the TDP space demonstrate mutually shaping relations between different calculative agencies.

According to Callon and Muniesa, these sorts of manipulations and transformations occur in both 'a very material sense, as in the case of a mechanical calculator' and are also 'at work in less mechanical situations' where the evolution of multiple entities is observable in a single space.[79] While our *manipulations and translations* occurred in wholly different contexts than those demonstrated by Callon and Muniesa, Figure 5 is intended to illustrate both *the material* *and less mechanical* situations they describe. In the context of complex engineering processes of technological development, it appears that the working of a calculative device hardly follows any particular order along separate moments. *Qualculations* are seemingly performed as interconnected and reciprocating engagements.

ORGANIZING ENCOUNTERS BETWEEN CALCULATIVE AGENCIES

A key characteristic of the mechanical arrangements organized within the TDP space can be drawn from composites of the SDP-report, shown on the right side of Figure 5. Here, distributed entities are organized from seemingly erratic negotiations of matters of concern, where entities are mechanically manipulated and transformed, according to the demands of a fluid (albeit centralized) SDP-report.[80] To cut through the erratic nature of these negotiations, we consider them as a calculated 'material and social effort to produce spatial practices appropriate to qualculation'.[81]

Viewing the SDP-report composites through this lens, the *GPS Motion Pack* and *Steering Robot* are clearly linked to *Tractors*, themselves an integral part of a center of calculation including *Prototypes*, *Test Specifications* and *Analytical Models*, all of which are housed within an *SDP-report* whose contents are (re)negotiated in interaction with the TRL device. The left side of Figure 5 illustrates a less mechanical arrangement. Here, working conceptions of functionality are grouped together, sometimes line by line (see Figure 3), under the *Purpose/Requirements of the Technology* heading of the TRL Assessment Template, so that their relations might be considered and addressed concurrently. This act 'materially associates [multiple] entities', to display their evolution simultaneously and allows the Assessment Group to (re)consider the relationships and effects of actors and intermediary objects *across* functional concepts.[82]

The TRL device's position at the center of the figure intends to illustrate how the TRL device's power rests in its 'quality for classifying, manipulating, and ranking' entities in a single space.[83] Arrows emanating from the device indicate omnidirectional encounters between the device and both types of arrangements. Here, new conceptualizations of functionality (e.g. *Stability*) are fostered as *Readiness Levels* are (re)negotiated. In turn these conceptualizations stipulate new intermediary objects (e.g. *Prototypes, Analytical Models*) with specific demands to reliability (e.g. *System Compatibility*), as proposed by the networks of specialized actors shown at the top of the figure (the Assessment Group and TDP Team – organized across arrangements to execute and interpret *encounters between agencies*).

ESTABLISHING RULES AND CONVENTIONS FOR ACCOUNTABILITY

According to current literature, TRL's *raison d'être* is as a figure of merit – it provides a number from which decisions can be made and risks mitigated. Though we disagree that this ability to generate a finalized number is TRL's *primary* strength, it does bring us to the third moment of a calculative device: establishing 'the rules or conventions that set the order in which [. . .] connections must be treated and taken into account'.[84] Here conventions are manifested as readiness levels TRL1 to TRL9, which are 'able to leave the calculative space and circulate elsewhere in an acceptable way (without taking with it the whole calculative apparatus)'.[85] Likewise, our case showed that Test Specifications, Analytical Methods, and Reports created to support these finalized numbers also left the calculative space to circulate elsewhere, as the evidence upon which finalized numbers were acknowledged. While Callon and Muniesa make no specific demand that the three moments of a calculative device occur sequentially, we find it interesting that TRL readiness definitions and finalized numbers (rules and conventions) were not confined to the third step of a calculative device but were (re)negotiated across Assessment Meetings. Perhaps this is related to the needs of the TDP Team to clarify conventions at early stages, given the expectations of the mature and bureaucratized organization of the product development spaces into which their activities will feed? As previously stated, the TRL device served as a *mandate* from which Senior Management's expectations (that a functional and reliable technology would later transition into a product development project) could be fulfilled. These expectations are certainly different from the more entrepreneurial situations found within market creation.[86]

Though TDP are not paced according to wholly linear templates, technologies are still meant to feed into future applications, the specificities of which are not always known. Moreover, yields contributing to these specifications are often identified and defined within the confines of the TDP space. Consequently, early TDP deliverables include defining the course of the project, its activities and presupposed results. A TDP Team (lacking a template and with limited knowledge of applications for which the technology is suitable) must establish its own *rules or conventions*, already from the project start. The most obvious example of this was the intervention into readiness level definitions instigated by the TDP Simulation Specialist. But it was also apparent when the TDP Manager and Mechanical Hardware Specialist first established *which* notions of functionality and reliability would be included in the TRL Template, *how* these notions would be defined, and *whose* expertise and influence would be included in assessments. Though the intentionally flexible structure placed on the TDP could help to explain the nonlinearity observed among the TRL device's three calculative moments, we propose that mutual shaping between the centralized TRL device and the distributed development and design activities occurring in the development space played a more significant role, by engendering conditions wherefrom the nonlinearity of calculative tasks arose. In contrast to its primary function as espoused in TRL literature, we find TRL's performance in defining and circulating heterogeneous, actors, conceptualizations and intermediary objects to be its real *tour de force*. Still, the stability of the centralized TRL device was not immune to effects generated via its interactions with distributed entities.

In a similar vein, Law describes how heterogeneously-engineered emergent objects (i.e. galleys) were also ‘disassociated into their components [. . .] in the face of stronger adversaries’.[87] In contrast to Law’s galleys, the TRL device was never fully *disassociated*. It was rather repurposed, first by TPM and MHS (to accommodate system compatibility) and later by SSS to incorporate level specific, predictive demands for staging transitions between readiness levels. This repurposing was characterized by a process of (re)negotiation. The TRL device both reduced and increased uncertainty for and around the technology for which it was deployed until stable (centralized) notions of functionality and reliability could be synthesized across the distributed objects, actors and conceptualizations characterizing the development space. This coincides well with Vinck’s observation that ‘actors undertake a work of alignment and articulation of resources in terms of the experiment and the manipulation to be carried out’ so that these might be integrated ‘into the life of the laboratory’.[88] Here the TRL device served as the center of calculation from which the case actors’ alignments, articulations, manipulations and integrations were made possible. No wonder then, that the three calculative moments seemed to shuttle nonlinearly – as part and parcel of how the TRL device was reconfigured and repurposed. Returning to Law, the three moments of a calculative device were, when facing disassociation, reassembled in a manner that could contribute to what was being built – in this case a functional and reliable steering technology.[89]

A PROVOKING, DIALOGIC INSTRUMENT – SHAPING AND RESHAPED IN A PROCESS OF DEVELOPMENT

In the hands of the TDP Manager, the TRL device showed strength as a provoking, dialogic instrument that produced agreement on the objects and conceptualizations it helped to mobilize and the problematizations these engendered. Looking to our narrative, there are at least two examples of the TRL device helping to configure the content and structure of the spaces wherein functionality and reliability of the technology were (re)negotiated.

The first example is the text on self-alignment, composed in plenum in the first Assessment Meeting and appended to the Template. This was the text upon which the Simulation & System Specialist would build his arguments for changing the Template’s readiness definitions. But it was also a reason these changes were later accepted by the Assessment Group. The second example stems from the TDP Manager’s attempt to frame improved energy consumption as a failed activity in the TRL Template, provoking dialogue and eventually a consensus around principle actions. The question so arises, how were these dialogues made possible? Was it the mandate provided by the TRL device, to continually gauge the readiness of transitions from (technology to potential product) and react accordingly, that allowed the TDP Manager to invite actors, set the agenda, and facilitate the TRL Assessment Meetings? As the division's preferred channel of communication for said transitions, the TRL device certainly strengthened the TDP Manager's position as spokesperson for Senior Management, helping him to mobilize actors, who could speak on behalf of other calculative agencies, to meet up and be held responsible. But the dialogic nature of these meetings also provided a stage from which calculative agencies could be displayed, potentially strengthening the mandate of other spokespersons. We suggest these participatory aspects of staging served to provoke manipulations of the conceptualizing process itself, where the forms the technology could later take were themselves delineated by and for this conceptualizing process. [90] While the relationship between reaction and self-alignment needed to be defined before these notions could be simulated and tested in stable prototypes, proving these notions also shackled the test specifications and analytical methods upon which proof was based to any future projects hoping to use the technology. This exemplifies how the TRL device, performing as a center of calculation, can both localize 'things, peoples and events, which are distant', while itself being localized by these same elements in a cycle of accumulation.[91] This is an important finding that demonstrates how, during this cycle, a centralized calculative device (TRL) and the distributed design and development activities which it wrought were shaped in a mutual process. As such, TRL performs as a *malleable* center.

Our focus is inspired by STS theory and methods that have been used elsewhere to illustrate how *facts* (e.g. notions of functionality and reliability) are developed through staged negotiation. Applying this focus to TRL revealed its constitutive, configurative, and transformative potential, and allowed us to view TRL as more than a scale for communicating *established* facts. According to Vinck: 'The "fact" rarely imposes itself. Researchers learn how to produce it and how to distinguish it from the artefact thanks to various manipulations and critical examination'. In our case these facts were produced and (de)stabilized through a process of (re)negotiation. A process both instigated and delimited by how TRL was deployed by the TDP Manager. As such, TRL played an integral and hitherto unexplored role in how '[t]he production of the agreement contributes to the production of results which will then be publicly affirmed'.[92]

CONCLUSION

At the start of this paper, we asked how the TRL figure of merit contributes to circumscribing, configuring, and coordinating technology development processes (in the hands of a technology manager) within industrial engineering organizations. Drawing on STS theory and methods we followed objects and actors to understand how the TDP Manager deployed TRL in an industrial case of engineering practice, so that we might illustrate its stabilizing role as a calculative device. To these ends we present the following findings for reflection.

1. *TRL Performs as a Calculative Device.* With few exceptions,[93] the current TRL literature focuses on its strength as 'a figure of merit', where various *stages* help to define project priorities, mitigate risk, act as milestones for moving products through development phases, and serve as benchmarks for communication at the launch of new technologies.[94] We propose a more accurate empirical account of TRL as a provoking, dialogic instrument for *staging* processes of technological development. Though the breadth of the TRL literature presupposes stable definitions for the specific stages, we found that the circumscribing and configuring powers of the TRL device were improved as it transitioned through a period of instable definitions.[95] This period of instability seemed to engender new problematizations, leading to (additional) credible statements about the technology and its status, and served to mobilize and stabilize the heterogeneous network of engineers, managers, test specifications, prototypes, methods of analysis, specialized equipment, and reports constituting the technology development project.

2. *Engineering Practice can benefit from STS theory and methods.* We argue that STS theory and methods (as utilized here) can contribute to a richer understanding of not just TRL, but other metric-based, decision-making concepts employed in industrial engineering practice. Our focus on the TRL device as a *calculative device* (considered not just as a series of finalized numbers, but the heterogenous network upon which these finalized numbers rest) and its deployment in the hands of a Technology Manager, revealed TRL properties hitherto unaddressed in the TRL literature. Drawing on Vinck's 'Approaches to the Ethnography of Technologies', the TDP Manager, gained deeper insights into the sociotechnical world of which he is part.[96] Taking root in day-to-day experiences, these insights were easily shared with colleagues and helped him to lead the TDP Team through a scope of action – as it was expanded and limited through the objects and actors that their problematizations engendered. This is not to be underestimated. WF has long sought ways in which the *ad hoc*, recursive nature of technology development might be conceptualized as a principal contribution to the highly structured stage-gate processes into which it feeds. As a potential endpoint of this search, the notion of *heterogeneous engineering* might also help technology managers and engineers to navigate the changing strategies of technology development processes.

3. *The three moments of a calculative device are continuously shaped and reshaped.* Though the notion of a *calculative device* was developed to address a process of *economic* network-stabilization, its three calculative moments can be extended to address a process of *technologic* network-stabilization. This extension rests upon the aim to which a calculative device is purposed: stabilizing a *center of calculation*. While Callon and Muniesa make no explicit demand for the linearity of the three moments, they do designate them sequentially. Considering the TRL device, we found these calculative moments recurrently nonlinear. We propose that *mutual*

shaping between the centralized TRL device and the distributed development and design activities occurring in the TDP space played a significant role in engendering the conditions wherefrom this nonlinearity arose. Furthermore, we found evidence to support a process of mutual shaping recurring between the moments themselves, here the aspects characterizing the moments were constantly (re)negotiated in processes of (de)stabilization.

LIMITATIONS AND IMPLICATIONS FOR ENGINEERING PRACTICE

As an auto-ethnographic empirical study, our case reveals much about the TRL device as deployed by a budding STS scholar in the technical role of technology manager within an industrial organization. Still, little is known about how TRL is employed to coordinate action in the gaggle of industrial, aerospace, and defense organizations within which it has been well documented as a figure of merit. It would be highly relevant to compare our single case study with other industrial cases of TRL in order to generalize our findings.

Drawing on ANT theory and methods to consider the performance of TRL as a calculative device helped the technology manager to engage reflexively with his own practice. Industry employs a plethora of other metric-based, decision-making concepts, all of which impose action through the problematizations they serve to engender and might similarly function as calculative devices (e.g. Failure Mode and Effects Analysis, Risk Scoreboards and Technology Forecasting). To further advance the STS perspective within engineering practice, we suggest that STS scholars (re)align themselves with the laboratories of industrial practice.[97] Better still, skilled technology managers and engineers could undertake similar auto-ethnographic studies. Though STS theory and methods are not presently widespread in engineering science, their practical application can be reasonably included in engineering education, as others have already shown.[98]

While the bulk of this paper considers TRL as a *(re)writing* and *calculative device*, we also found meaning in the other STS notions of objects and devices mentioned earlier. The *boundary object* sheds light on how TRL became, in some respects, an invisible infrastructure structuring the relation between different social worlds. Though they interpret it differently, TRL is utilized by both the TDP Team and Top Management in a symbiotic relation (as when 'more demanding TRL definitions' reduced pre-supposed efficacy and were leveraged by the TDP Manager to gain additional resources). Still, not all the data sustains interpretations of TRL as a boundary object. Viewing the TRL device as an *intermediary object,* reciprocally shaping the circulation of other intermediary objects, is thus relevant to grasp additional aspects of the empirical data (e.g. as TRL fostered negotiations of what 'good engineering' does and how it allows an engineer to situate his/her specific expertise as necessary).

NOTES

1. Mankins, "Technology Readiness and Risk Assessments" and; "Technology Readiness Assessments."
2. Clausen and Gunn, "From the Social Shaping of Technology to the Staging of Temporary Spaces of Innovation."
3. For examples, see Clausen and Yoshinaka, "The Role of Devices," "Sociotechnical Spaces," and "Staging Socio-technical Spaces."
4. See Latour and Woolgar, *Laboratory Life*.
5. Callon and Muniesa, "Peripheral Vision."
6. See Trevelyan, "Reconstructing Engineering from Practice." 5, 7.
7. See Vinck, "Taking Intermediary Objects."
8. Ibid., 25
9. For examples, see: Broberg, Andersen, and Seim, "Participatory Ergonomics in Design Processes," Hussenot and Missionier, "A Deeper Understanding," Lee and Amjadi, "The Role of Materiality," and Rau, Neyer, and Möslein, "Innovation Practices and their Boundary-crossing Mechanisms."
10. Webster and Gardner, "Aligning Technology and Institutional Readiness."
11. See Vinck, "Taking Intermediary Objects," and "Accessing Material Culture."
12. The corresponding author qualifies as a *complete member researcher*: Adler and Adler, *Membership Roles in Field Research*, 67–81. He has been employed in technology development at the host company since 2005 and identifies as an *auto-ethnographer*, possessing "the qualities of often permanent self-identification with a group and full internal membership," as recognized by both himself and the group of whom he is a part. Hayano, "Auto-ethnography," 100.
13. Law, "Actor Network Theory and Material Semiotics," 141.
14. For similar endeavors, see: Hansen and Clausen, "Management Concepts and the Navigation of Interessement Devices," and Vagn Jensen, Clausen, and Gish, "Three Perspectives on Managing Front End Innovation."
15. Vinck, *Everyday Engineering*, 3.
16. Ibid.
17. All dialogues were translated by the authors from Danish, where translations were edited for clarity and brevity and approved by the cited individuals.
18. Vinck, *Everyday Engineering*.
19. Vinck, *Engineering Practices*, k.
20. Clausen and Gunn, "From the Social Shaping of Technology to the Staging of Temporary Spaces of Innovation," 87.
21. Ibid., 88.
22. See Mankins, "Technology Readiness and Risk Assessments," 1208.

23. Sadin, Povinelli, and Rosen, "The NASA Technology Push towards Future Space Mission Systems."
24. For the 9-point scale see Mankins, "Technology Readiness Levels." For TRL's proliferation see Olechowski, Eppinger, and Joglekar, "Technology Readiness Levels at 40."
25. Merriam-Webster Incorporated, "Figure of Merit," < https://www.merriam-webster.com/diction ary/figure%20of%20merit > Accessed February 3, 2019.
26. Murchie et al., "Compact Reconnaissance Imaging Spectrometer."
27. E.g. Arbjerg et al.,, *Hydraulische Lenkeinheit*.
28. Danfoss A/S, *Proprietary Company Document (in re Work Functions Division TRL Scale)*.
29. Cf. Danfoss A/S, *Proprietary Company Document (in TRA Guidelines)*.
30. Danfoss A/S, *Proprietary Company Document (in re Milestone Plan)*.
31. Cooper, "Perspective: The Stage-Gate® Idea-to-Launch Process."
32. Danfoss A/S, *Proprietary Company Document (in re Project Milestone Deliverables)*.
33. For a critique of categories of 'basic' and 'applied' science using examples from micro-processes of Nobel-prize winning research, see Narayanamurti and Odumosu, *Cycles of Invention and Discovery*. For a proposal to replace 'stages and gates' with 'epochs and the shocks that initiate transitions' in management within the NASA innovation ecosystem, see Szajnfarber and Weigel, "A Process Model of Technology Innovation in Governmental Agencies," 59.
34. Mankins, "Technology Readiness and Risk Assessments," 1209.
35. See: Garg et al., "Using TRLs and System Architecture," Olechowski, Eppinger, and Joglekar, "Technology Readiness Levels at 40,"and Tomaschek et al., "A Survey of Technology Readiness Level Users."
36. Vinck, *Engineering Practices*, b.
37. Bowen, "Grounded Theory and Sensitizing Concepts," 2.
38. Callon, "Some Elements of a Sociology of Translation." 63, 62.
39. Vinck, "Accessing Material Culture by Following Intermediary Objects," 93.
40. Star and Griesemer "Institutional Ecology, Translations and Boundary Objects," 390.
41. Ibid., 389.
42. Vinck, "Accessing Material Culture by Following Intermediary Objects," 93.
43. Star and Griesemer "Institutional Ecology, Translations and Boundary Objects," 392, 393.
44. Vinck, "Accessing Material Culture by Following Intermediary Objects," 94.
45. Ibid., 93–4.
46. Star and Griesemer "Institutional Ecology, Translations and Boundary Objects," 393.
47. Vinck, "Accessing Material Culture by Following Intermediary Objects."
48. Star and Griesemer "Institutional Ecology, Translations and Boundary Objects," 408.
49. Vinck, Jeantet, and Laureillard, "Objects and Other Intermediaries," 302.
50. Ibid., 299.

51. Clausen and Gunn, "From the Social Shaping of Technology to the Staging of Temporary Spaces of Innovation," 77.
52. Vinck, *The Sociology of Scientific Work*, 200.
53. Callon, "Writing and (Re) Writing Devices," 193.
54. Ibid., 212.
55. Callon and Muniesa, "Peripheral Vision," 1231.
56. Callon and Law, "On Qualculation, Agency and Otherness," 717. For *qualculation* see Cochoy, *Une sociologie du packaging ou l'âne de Buridan face au marché*.
57. Callon and Muniesa, "Peripheral Vision," 1231.
58. Ibid., 1245.
59. Cf. Latour, *Science in Action*, 222:

    > All the distinctions one could wish to make between domains (economics, politics, science, technology, law) are less important than the unique movement that makes all of these domains conspire towards the same goal: a cycle of accumulation that allows a point to become a centre by acting at a distance on many other points.

    In this case, the TRL device serves as the point from which actions pertaining to the design, development, dissemination and adaption of a novel technology are negotiated across notions of functionality and reliability – that efficacy (*readiness*) can be realized, communicated and leveraged.
60. An annual event open to all Danfoss employees seeking to develop ideas for breakthrough products in infrastructure, energy, climate and food technologies.
61. The first comprises a combination of GPS receivers and inertial sensors for controlling and recording (non)autonomous vehicle tests. The latter is an autonomous system for applying accurate and repeatable inputs to a vehicle's steering system.
62. Concerning specialized methods of testing and analysis, e.g. ISO, *7401:2011. Road Vehicles*.
63. For more on demos in commercial and technological settings, see Rosental, "Toward a Sociology of Public Demonstrations."
64. In WF, an SDP-report is a repository housing all relevant information for a *steering development project*, including a finalized report documenting the *Purpose, Background, Procedures, Analyses*, *Conclusion* and *Date-of-completion* for said activity. While finalized SDP-reports are generally accepted as evidence upon which future analyses and conclusions can be constructed and confirmed, unfinalized SDP-reports contain information still commuting between *commissioning* and *mediating* roles.
65. Callon and Muniesa, "Peripheral Vision," 1242.
66. Ibid., 1238. An ideal *calculative agency* will "establish a long, yet finite list of diverse entities," within a space that is open enough to accommodate a multitude of possible classifications and reclassifications, that the "procedures and algorithms" most likely to

multiply "possible hierarchies and classifications" between these entities might be formalized.

67. TRL 3 (per 9 June 2017): "Analytical or Experimental Critical Functions and/or proofs of concept exist (including FEA or mathematical modelling activities)."
68. TRL 4 (per 9 June 2017): "Specific Technology Prototype mock-ups or similar components have been tested in WF Laboratories."
69. TRL 5 (per 9 June 2017): "Specific Technology Prototypes or have been validated in a relevant environment and/or application."
70. Cf. Clausen and Yoshinaka, "The Role of Devices in Staging Front End Innovation."
71. See Latour, *Reassembling the Social*, 116: A matter of concern

> *is the thing itself that has been allowed to be deployed as multiple*, and thus allowed to be grasped through different viewpoints, before being possibly unified in some later stage depending on the abilities of the collective to unify them.

72. TRL 3 (per 23 June 2017): "Critical functions are described. Analytical and experimental activities are defined, and proofs of concept exist."
73. TRL 5 (per 23 June 2017): "Specific Technology Prototypes have been validated in a relevant environment and/or application and the critical functions have been validated analytically."
74. Law, "Technology and Heterogeneous Engineering."
75. Ibid., 109.
76. Callon and Muniesa, "Peripheral Vision." 1242.
77. Ibid., 1231.
78. Ibid., 1242.
79. Ibid., 1231.
80. *Erratic* due their 'uncertain and highly disputed character', matters of concern are 'real, objective, atypical, and above all, interesting agencies', more readily understood as gatherings than objects. See Latour, *Reassembling the Social*, 114.
81. Callon and Law, "On Qualculation, Agency and Otherness," 718.
82. Callon and Muniesa, "Peripheral Vision," 1231.
83. Callon and Law, "On Qualculation, Agency and Otherness," 720.
84. Callon and Muniesa, "Peripheral Vision," 1242.
85. Ibid.
86. Ibid., 1236–7.
87. Law, "Technology and Heterogeneous Engineering," 111.
88. Vinck, *The Sociology of Scientific Work*, 199.
89. Law, "Technology and Heterogeneous Engineering."
90. Cf. Vinck, *The Sociology of Scientific Work*, 220. "Conceptual work involves a broad material exercise in writing, correction, deletion and rewriting, on paper, on the board and on computer. Some of the "abstract" work can, therefore, be entered in its materiality."

91. Latour, *Science in Action*, 220.
92. Vinck, *The Sociology of Scientific Work*, 203–4.
93. For another sociotechnical take on TRL, see Webster and Gardner, “Aligning Technology and Institutional Readiness.”
94. E.g. Garg et al., “Using TRLs and System Architecture to Estimate Technology Integration Risk.”
95. Webster and Gardner, “Aligning Technology and Institutional Readiness,” 1230: Exceptionally, Webster and Gardner consider sociotechnical aspects of how ‘readiness looks at the specific contexts within which innovation is engaged with and made sense of, and how, in doing so, is often adapted in order to be adopted.’
96. See Vinck, *Everyday Engineering*, 203–26.
97. Cf. Ibid. and “Engineering Practices.”
98. For examples, see: Juhl and Lindegaard, “Representations and Visual Synthesis in Engineering Design,” Legardeur, Zephir, and Minel, “How to Analyse Collaborative Practices of Engineering Students?” and Petersen and Buch, “Making Room in Engineering Design Practices.”

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REFERENCES

Adler, Patricia A., and Peter Adler. *Membership Roles in Field Research*, 6 Vols. Thousand Oaks: Sage, 1987.

Arbjerg, N., C. A. Bates, P. Ennemark, M. Frederiksen, and C. M. Olesen. *Hydraulische Lenkeinheit*. Patent No. DE 102017109798, 2018.

Bowen, Glenn A. "Grounded Theory and Sensitizing Concepts." *International Journal of Qualitative Methods* 5, no. 3 (2006): 12–23.

Bresnen, Mike, and Chris Harty. "Editorial: Objects, Knowledge Sharing and Knowledge Transformation in Projects." *Construction Management and Economics* 28, no. 6 (2010): 549–555.

Broberg, Ole, Vibeke Andersen, and Rikke Seim. "Participatory Ergonomics in Design Processes: The Role of Boundary Objects." *Applied Ergonomics* 42, no. 3 (2011): 464–472.

Callon, Michel. "Writing and (Re) Writing Devices as Tools for Managing Complexity." In *Complexities: Social Studies of Knowledge Practices*, edited by Annemarie Mol, and John Law, 191–217. Durham: Duke University Press, 2002.

Callon, Michel. "Some Elements of a Sociology of Translation." In *Technoscience: The Politics of Interventions*, edited by Kristin Asdal, Brita Brenna, and Ingunn Moser, 57–78. Oslo: Oslo Academic Press, 2007.

Callon, Michel, and John Law. "On Qualculation, Agency and Otherness." *Environment and Planning D: Society and Space* 23, no. 5 (2005): 717–733.

Callon, Michel, and Fabian Muniesa. "Peripheral Vision: Economic Markets as Calculative Collective Devices." *Organization Studies* 26, no. 8 (2005): 1229–1250.

Clausen, Christian, and Wendy Gunn. "From the Social Shaping of Technology to the Staging of Temporary Spaces of Innovation – A Case of

Participatory Innovation." *Science and Technology Studies* 28, no. 1 (2015): 73–94.

Clausen, Christian, and Yutaka Yoshinaka. "Sociotechnical Spaces: Guiding Politics, Staging Design." *International Journal of Technology and Human Interaction (IJTHI)* 1, no. 3 (2005): 44–59.

Clausen, Christian, and Yutaka Yoshinaka. "Staging Socio-technical Spaces: Translating Across Boundaries in Design." *Journal of Design Research* 6, no. 1–2 (2007): 61–78.

Clausen, Christian, and Yutaka Yoshinaka. "The Role of Devices in Staging Front End Innovation." In First International Conference on integration of design, engineering and Management for innovation. FEUP Faculty of Engineering and Management of the University of Porto, 2009.

Cochoy, Franck. *Une sociologie du packaging ou l'âne de Buridan face au marché: Les emballages et le choix du consommateur*. Paris: Presses universitaires de France, 2002.

Cooper, Robert G. "Perspective: The Stage-Gate® Idea-to-Launch Process – Update, What's New, and

NexGen Systems." *Journal of Product Innovation Management* 25, no. 3 (2008): 213–232.

Danfoss A/S. *Proprietary Company Document (in re WF Division TRL Scale)*. 2012.

Danfoss A/S. *Proprietary Company Document (in re TRA Guidelines)*. 2016.

Danfoss A/S. *Proprietary Company Document (in re Milestone Deliverables)*. 2017.

Danfoss A/S. *Proprietary Company Document (in re Project Milestones)*. 2017.

Danfoss A/S. *Steering General, Steering Components*. 2017.

Downey, Gary L. "What is Engineering Studies for? Dominant Practices and Scalable Scholarship." *Engineering Studies* 1, no. 1 (2009): 55–76.

Garg, Tushar, Steven Eppinger, Nitin Joglekar, and Alison Olechowski. "Using TRLs and System Architecture to Estimate Technology Integration Risk. " DS 87-3 Proceedings of the 21st International Conference on engineering design (ICED 17) Vol 3: product, Services and systems design, Vancouver, Canada, August 21–25, 2017.

Hall-Andersen, Lene Bjerg, and Ole Broberg. "Integrating Ergonomics into Engineering Design: The Role of Objects." *Applied Ergonomics* 45, no. 3 (2014): 647–654.

Hansen, Per Richard, and Christian Clausen. "Management Concepts and the Navigation of Interessement Devices: The Key Role of Interessement Devices in the Creation of Agency and the Enablement of Organizational Change." *Journal of Change Management* 17, no. 4 (2017): 344–366.

Hayano, David M. "Auto-ethnography: Paradigms, Problems, and Prospects." *Human Organization* 38, no. 1 (1979): 99–104.

Hussenot, Anthony, and Stéphanie Missonier. "A Deeper Understanding of Evolution of the Role of the Object in Organizational Process: The Concept of 'Mediation Object'." *Journal of Organizational Change Management* 23, no. 3 (2010): 269–286.

ISO. *7401:2011. Road Vehicles – Lateral Transient Response Test Methods – Open-Loop Test Methods*. Geneva: International Organization for Standardization, 2011.

Juhl, Joakim, and Hanne Lindegaard. "Representations and Visual Synthesis in Engineering Design." *Journal of Engineering Education* 102, no. 1 (2013): 20–50.

Latour, Bruno. "Give me a Laboratory and I will Raise the World." In *Science Observed: Perspectives on the Social Study of Science*, edited by Karin D. Knorr-Cetina, and Michael Mulkay, 141–170. Thousand Oaks: Sage, 1983.

Latour, Bruno. *Science in Action: How to Follow Scientists and Engineers through Society*. Cambridge: Harvard University Press, 1987.

Latour, Bruno. *The Pasteurization of France*. Cambridge: Harvard University Press, 1993.

Latour, Bruno. *Reassembling the Social: An Introduction to Actor-Network Theory*. Oxford: Oxford University Press, 2005.

Latour, Bruno, and Steven Woolgar. *Laboratory Life: The Social Construction of Scientific Facts*. Beverly Hills: Sage, 1979.

Law, John. "Technology and Heterogeneous Engineering: The Case of Portuguese Expansion." In *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, edited by Wiebe Bijker, Thomas P. Hughes, and Trevor J. Pinch, 111–134. Cambridge: MIT Press, 1987, 1989.

Law, John. "Actor Network Theory and Material Semiotics." In *The New Blackwell Companion to Social Theory*, edited by Bryan S. Turner, 141–158. Hoboken: John Wiley & Sons, 2008.

Lee, Ching-Fang, and Mansour Amjadi. "The Role of Materiality: Knowing through Objects in Work Practice." *European Management Journal* 32, no. 5 (2014): 723–734.

Legardeur, Jérémy, Olivier Zephir, and Stephanie Minel. "How to Analyse Collaborative Practices of Engineering Students?" In DS 46: Proceedings of EandPDE 2008, the 10th International Conference on engineering and product design education, Barcelona, Spain, September 4–5, 2008.

Mankins, John C. *Technology Readiness Levels: A White Paper April 6, 1995*. Redstone Arsenal, AL:

Advanced Concepts Office, Office of Space Access and Technology: NASA, 1995.

Mankins, John C. "Technology Readiness and Risk Assessments: A New Approach." *Acta Astronautica* 65, no. 9–10 (2009): 1208–1215.

Mankins, John C. "Technology Readiness Assessments: A Retrospective." *Acta Astronautica* 65, no. 9–10 (2009): 1216–1223.

Narayanamurti, Venkatesh, and Tolu Odumosu. *Cycles of Invention and Discovery*. Cambridge: Harvard University Press, 2016.

Olechowski, Alison, Steven D. Eppinger, and Nitin Joglekar. "Technology Readiness Levels at 40: A Study of State-of-the-Art Use, Challenges, and Opportunities." In Proceedings of Portland International Conference on Management of engineering and technology (PICMET), August 2015, 2015.

Petersen, Rikke Premer, and Anders Buch. "Making Room in Engineering Design Practices." *Engineering Studies* 8, no. 2 (2016): 93–115.

Rau, Christiane, Anne-Katrin Neyer, and Kathrin M. Möslein. "Innovation Practices and Their Boundary-Crossing Mechanisms: A Review and Proposals for the Future." *Technology Analysis & Strategic Management* 24, no. 2 (2012): 181–217.

Rosental, Claude. "Toward a Sociology of Public Demonstrations." *Sociological Theory* 31, no. 4 (2013): 343–365.

Sadin, Stanley R., Frederick P. Povinelli, and Robert Rosen. "The NASA Technology Push towards Future Space Mission Systems." Space and Humanity. selected Proceedings of the 39th International Astronautical Federation Congress, Bangalore, India, 8–15 October 1988, 1989.

Star, Susan Leigh, and James R. Griesemer. "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39." *Social Studies of Science* 19, no. 3 (1989): 387–420.

Szajnfarber, Zoe, and Annalisa L. Weigel. "A Process Model of Technology Innovation in Governmental Agencies: Insights from NASA's Science Directorate." *Acta Astronautica* 84 (2013): 56–68.

Tomaschek, Katharina, Alison Olechowski, Steven Eppinger, and Nitin Joglekar. "A Survey of Technology Readiness Level Users." *INCOSE International Symposium* 26 (2016): 2101–2117.

Trevelyan, James. "Reconstructing Engineering from Practice." *Engineering Studies* 2, no. 3 (2010): 175–195.

Vagn Jensen, Anna Rose, Christian Clausen, and Liv Gish. "Three Perspectives on Managing Front End Innovation: Process, Knowledge and Translation." *International Journal of Innovation Management* 22, no. 7 (2018): 1850060.

Vinck, Dominique (ed.). *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press, 2009.

Vinck, Dominique. *The Sociology of Scientific Work*. Cheltenham: Edward Elgar Publishing, 2010. Vinck, Dominique. "Taking Intermediary Objects and Equipping Work into Account in the Study of Engineering Practices." *Engineering Studies* 3, no. 1 (2011): 25–44.

Vinck, Dominique. "Accessing Material Culture by Following Intermediary Objects." In *An Ethnography of Global Landscapes and Corridors*, edited by Loshini Naidoo, 89–108. Chicago: InTech Publishing, 2012.

Vinck, Dominique. "Engineering Practices." *Revue d'anthropologie des connaissances* 8, no. 2 (2014): á–s.

Vinck, Dominique, Alain Jeantet, and Pascal Laureillard. "Objects and Other Intermediaries in the Sociotechnical Process of Product Design: An Exploratory Approach." *The Role of Design in the Shaping of Technology* 5 (1996): 297–320.

Webster, Andrew, and John Gardner. "Aligning Technology and Institutional Readiness: The Adoption of Innovation." *Technology Analysis & Strategic Management* 31, no. 10 (2019): 1229–1241.

Appendix B. Staging with Objects: Translation from Technology to Product Development

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Abstract

This auto-ethnographic study considers the transition from technology to product development in an industrial case led by the author. The chapter reflects on 'staging with objects' as a practice by which entities, defined as networks composed of humans and non-humans as well as material and immaterial objects, are assembled to perform in processes of translation. This notion of staging intends to increase understanding of how problematizations and qualifications concerning the suitability of an invention for product specific applications are negotiated across heterogenous networks. In contrast to mechanistic management perceptions, the chapter presents a a fresh perspective on the active use of objects in the practices of managers and engineers occupied with transitions from invention to commercialization. In conclusion, I present four points to help technology managers and engineers utilize staging with objects as an engineering practice.

Keywords: ANT; Auto-ethnography; Intermediary Objects, Staging, Technology Development, Translation

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INTRODUCTION

The successful transition of inventions from technology development to product development is a well-known challenge in both industrial practice and management scholarship. Mainstream management literature provides numerous frameworks and process models targeting industrial practitioners who seek to effectively span transitions from invention to commercialization. Nevertheless, this body of literature often neglects how technology managers and engineers practically negotiate the opportunities and limitations which arise *through* interaction with these frameworks and process models.

In this chapter, I propose that problematizations concerning the suitability of a technology for product specific applications are (re)negotiated across heterogenous networks as the developing technology encounters new actors and changing notions of functionality and reliability. Furthermore, I submit that objects play significant roles in how such negotiations are staged, and that sensitization towards this process can benefit technology managers and engineers tasked with such translations. These are not radical propositions. Building on the 'laboratory studies' of Latour and Woolgar (1979), Vinck (2009: 1) argues that by focusing on technical reality, 'a different vision of technology will emerge—a vision that technicians should find easy to understand because it will be based on their day-to-day life'.

Following an industrial case, I consider the transition from a *technology development project* (TDP) to a *product development project* (PDP) as a process of alignment across distinct (albeit mutually shaping) networks tasked with separate goals. Henceforth, I define technology development as a collection of diverse activities whereby the functionality and reliability of inventions are negotiated and improved across specialized networks to enable them to be incorporated into predetermined product-specific applications. As such, a TDP differs significantly from the structured PDP into which it feeds. PDPs focus on commercialization and are based on the assumption that technologies with sufficiently high levels of functionality and reliability can coalesce with a viable business case through structured customer interactions (see process models described by Cooper 2008).

This chapter responds to a limited understanding of the roles of objects within engineering management practice and how they are staged by managers and engineers. In mainstream literature, the transition from technology to product development is viewed as an exercise of idea identification, selection and maturation in a mostly orderly and mechanistic process (see for example, Cooper 2008; Florén and Frishammar 2012; Markham et al. 2010; Verworn et al. 2008). This scholarship claims to serve engineering work, yet does not always embrace or address the contents of such work. In mainstream management models, it is typically a management team coordinating how work is 'staged' (defined in Chapter 2 of this book as 'the inclusion/exclusion of actors, material and symbolic objects and concerns in a space and the construction of boundaries defining the space of development'). Often, this staging is framed as occurring through the proxy of a project manager or 'champion' equipped with an assumedly stable set of commercial criteria and a team of supporting specialists. Still, management literature mostly ignores the fact that 'models are not neutral but offer certain framings, contribute translations and act as sensemaking devices' (Clausen and Yoshinaka 2009: 1), and neglects how more mundane objects like prototypes mutually shape commercial criteria.

In contrast, this chapter focuses on the negotiations whereby technology managers and engineers accommodate changing scopes of action, with a focus on how a variety of objects help and impede translations as they are 'configured, stabilized and facilitated' (Clausen and Yoshinaka 2009: 4) throughout the staging process. Objects are interesting because they enable us to look at staging within engineering practice, as a complement to the management-centric staging found in management models. I use the term 'staging with objects' to highlight the reciprocal nature of what diverse actors do with shared objects, and how such exchanges (un)intentionally (dis)align the networks into which the objects are assembled.

This chapter is organized as follows. In the next section, I briefly introduce my analysis of 'staging with objects', including my research method and background information about the company. Then, I present a case highlighting the roles of objects involved in a project's translation from technology to product development. I follow this with a discussion of how objects are staged across heterogeneous networks, and conclude by elaborating on staging with objects as an engineering practice.

ANALYZING STAGING WITH OBJECTS

I reflect on 'staging' as a practice by which *entities*, defined as networks composed of humans and non-humans, as well as material and immaterial objects, are materialized and (re)assembled to perform in processes of translation. An engineering report is such an example, where finite relationships between standards, prototypes, measurements, test rigs and analytic methods are assembled and materialized in a written document. My reflections are rooted in classic actor-network theory (ANT) and the work of Clausen and Yoshinaka (2009: 2), who considered 'the role which devices play in the managing of FEI, with inspiration from science and technology studies . . . to examine and discuss devices that intervene at the front end'. Clausen and Yoshinaka considered staging from an academic perspective by observing, participating and interviewing to make sense of industrial practice. I exploit their notion to reflect on my own practice, combining insights as a technology manager employed in industry with an academic analytic perspective.

In this chapter, I view innovation as a process of translation: a movement between the practicalities of invention and commercialization, where the networks comprising such practicalities are inevitably displaced. To substantiate these aspects of translation, I align with scholars in science and technology studies (STS). Within this community, the notion of heterogeneity describes how the 'stability and form of artifacts should be seen as a function of the interaction of heterogeneous elements as these are shaped and assimilated into a network' (Law 1987 [2012]: 113). Heterogeneity thereby emphasizes 'material practices that generate the social' (Law 2009: 148), to describe '*how* relations assemble or don't' (Law 2009: 141). Furthermore, I consider technology and product development to be two distinct, albeit mutually shaping endeavours with shared social and material elements and dynamic ends. To analyse such translations, Vinck et al. (1996) propose using intermediary objects to help identify 'actors and characterise the forms of organisation and coordination, and the agreements binding them' (Vinck 2012: 91). Vinck et al. (1996) differentiate two types of intermediary objects: 'commissioning objects' translating goals into results, and 'mediating objects' instigating action and negotiation. This represents a network perception of the nature of objects, where 'objects are an effect of stable arrays or networks of relations' (Law 2002: 91). An important implication of this view is that 'innovation' takes place across and through numerous networks, where objects are designed and assembled to perform in interaction with other networks.

RESEARCH METHOD AND BACKGROUND

As an 'auto-ethnographer' (Hayano 1979: 100), I possessed 'qualities of often permanent self-identification with a group and full internal membership' in the networks considered. Building on these relations, I gathered empirical data from (inter)company communications, standards and specifications, journals, and audio recordings. In my role as a technology development project manager, I also co-authored the patents, test specifications, and whitepaper described herein. Analytically, I draw on ANT, which: 'treat[s] everything in the social and natural worlds as a continuously generated effect of the webs of relations within which they are located. It assumes that nothing has reality or form outside the enactment of those relations' (Law 2009: 141). To avoid confusion, I use 'object' to denote an actor-network that is stable or 'punctualized'[45] and 'elements' to denote the (un)stable 'arrays or networks of relations' (Law 2002) comprising these objects, such that each object is considered to be a heterogenous network of elements.

The setting for this study, Danfoss Power Solutions ApS (DPS), is a global leader in the industry in which it operates, providing complete hydraulic systems for the agriculture, infrastructure and material handling markets. In the Work Functions (WF) division, a TDP spans diverse, specialized networks, such as the division's engineering, production, sales, purchasing and leadership teams and its customers. Here, inventions are meant to feed into

[45] Punctualization: 'The process by which complex actor-networks are black boxed and linked with other networks to create larger actor-networks' (Callon 1991: 153).

future applications, the specificities of which are not always known and yields contributing to these specifications are identified and defined within the confines of the TDP. Even though assumptions regarding future uses of technology take root in a finite and heterogeneous network of objects and relationships which are assembled and verified according to company and industrial norms, these assumptions are still challenged as the technology moves towards the well-defined application-specific considerations of a product development process such as that outlined by Cooper (2008). Here, new actors and contextualizations, such as market players with diverging product programmes and architectures, can alter existing notions of functionality and reliability, thereby destabilising the objects and relations upon which initial assumptions rest. In the next section, I present a specific case documenting the transition of a TDP to a PDP.

AN INDUSTRIAL CASE OF TRANSLATION

In this case, I managed a TDP with the aim of maturing a novel technology that would make hydrostatic steering safe and comfortable at increased speeds. At one point, most aspects of the technology were evaluated as having high readiness for commercialization in multiple *technology readiness assessments* (TRAs; see Mankins 2009). Hoping to capitalize on this progress, the business unit vice president met with the engineering director and the TDP team to align the product strategy and discuss 'how technology development activities could more quickly transition into product development'.

At this juncture, the 'launch goals and strategy' were still unclear. Although the sales team had facilitated several technology demonstrations at company and customer test tracks, the 'scope and sequence' of possible vehicle systems into which customers might implement the technology remained uncertain. Ascertaining this scope and sequence requires specific commitments between the division and its customers, and these commitments presuppose high levels of technology readiness before solutions can be discussed. Furthermore, implementing novel technologies into complex off-highway mobile equipment often requires alignment with any *other* significant changes to vehicle architectures in the customer pipeline. Although the new technology was supposedly far enough along to seek the customer commitments and alignments necessary to confirm a preliminary business case, the TDP and sales teams had not requested top management's approval to initiate such negotiations with customers. Referring to the TDP team's 'impressive TRA results', the vice president was ready to begin these negotiations. He asked the sales team and I to develop a whitepaper describing preliminary 'pilot customer considerations' for presentation to the division's top management.

Over the following weeks, I set up and facilitated recurring 'whitepaper meetings' with the TDP team, the engineering director, the sales director and sales managers to document pilot customer considerations in the contexts of: (a) the preliminary business case from which the

TDP had sprung; (b) general characteristics of the hydraulic steering market, including their relevance to the technology; and (c) any necessary customer-specific considerations, commitments and alignments we could identify. After each meeting, I (re)composed sections of the whitepaper and sent them to the sales director and sales managers for review and revision. The original text, revisions and comments were then (re)negotiated in plenary discussions, after which I would (re)write sections of the whitepaper and (re)send them out for review or revision together with any supplementary notes, documents or pictures.

ALIGNING READINESS WITH COMMERCIALIZATION

Early in the project, the TDP and sales teams agreed the technology project would initially span two functional principles encompassing numerous variants. The first principle was purely hydraulic. The second principle was an electro-hydraulic solution. Accordingly, the TDP team developed and submitted nine patent applications covering the variety of vehicle architectures deemed relevant via experiments, customer discussions and demonstrations. Although both principles had been discussed and tested at length, both internally and externally with customers, the TDP team was mostly focused on single variant of the first principle, with intentions to develop other principles and variants later.

Prior to meeting with top management, the sales manager revealed unexpected news. While reviewing specific considerations, commitments and alignments for the whitepaper, a pilot customer wished to consider implementing the new technology across-the-board. Consequently, the functionality and reliability of the technology would need to span the customer's entire relevant portfolio before commitments to application-specific implementations could be made. Furthermore, a portion of previously unconsidered vehicles required a third type of steering unit (hereafter, the third principle). This meant three principles needed to be developed instead of two, and an implementation plan had to be created for all three before applications of the technology could be identified and considered. Although the third principle had been drafted earlier (via patents, experiments and discussions with customers), technical complexity and sales forecasts had rendered it to the project's fringes. It existed only as a proof-of-concept. The following exchange[46] highlights the challenges faced by the team.

> TDP Mechanical Hardware Specialist: We didn't plan to mature two, let alone three principles simultaneously. Maybe there's synergy between the second and third principles, assuming our focus can span their consecutive development. But

[46] Quotes were translated by the author from Danish (where necessary), edited for clarity and brevity and approved by cited individuals.

> that's a serious undertaking! It doesn't coincide with the speedy transition from technology to product development.
>
> Sales Manager [interjecting]: But it's the transition required for any realistic business case. Our customer wants plans to develop and deliver all three before committing.
>
> TDP Manager: This places extra, unexpected demands on our technology readiness. It negates our plan to develop the different principles piecewise. This does not coincide with what we promised top management.

Indeed, the division's top management found the news surprising and disappointing: 'Why wasn't the second principle further along?' They also expressed concerns about the third principle elaborated in the whitepaper. According to project assumptions, the technology was also feasible for this tractor market segment: 'So where was the plan for variants distinguishing this market?' In closing, the division president defined a new agenda:

> You've made impressive progress with aspects of the technology, but relationships between patents, design and test activities, and commercialization are still unclear . . . A necessary market remains undefined . . . The timing of the new variant is a surprise. Maybe we needed to achieve a certain readiness before mapping the market . . . but from now on, commercialization must drive development. The TDP manager will continue to lead development until we identify a PDP manager . . . In the meantime, sales will focus on developing a robust business case.

A few weeks later the new PDP manager joined the project. He worked closely with the sales director and his managers to redevelop the business case while I facilitated tests and analyses in preparation for the next readiness assessment. After a four-week overlap, the PDP manager took over coordination of development activities, with a mandate to transition into a PDP when the business case was complete.

RE-ALIGNING SELF-ALIGNMENT

A month later, I met with the PDP manager to discuss his progress. He said: 'As you know, we thought the new technology was most suitable for a specific hydraulic system. We didn't think its other functionalities were easily separated from self-alignment. Placing much of the market temporarily out-of-reach.' I did remember. These were key considerations in patents for the second and third principles. Moreover, not all of the principles were cost effective across the different hydraulic systems. The PDP manager continued:

> Not all customers want the first principle at high-speed. Not always because of cost, for some OEMs it's also their niche . . . The good news is, we can probably

> deliver third principle functionality by reducing self-alignment characteristics of the first principle.

This was big news. A variant for the third principle market was not developed when I left the TDP. What happened? In tractor tests of the newest prototype, specialists noticed poorer than expected performance of self-alignment with other functions mostly performing as they should. The mechanical hardware specialist explained:

> It was buried in the prototype's valving system. A manufacturing error changed a dimension by a few microns. Revisiting the patented hydraulic diagrams, making calculations and analysing test data, we realized it was possible to tune the first and second principles' self-alignment, to where they perform as a *de facto* third principle steering unit with negligible effects on other functions . . . Simulations are promising . . . We've ordered prototypes and tests.

Later, the PDP manager told me:

> If the specialists are right, a business case is close. We still need to develop the third principle for implementation with pilot customers, but we can tune self-alignment in the design and validation process towards developing the solution . . . Our readines*s* is back on track! I'm working with sales and top management on launch considerations for the new business case.

DISCUSSION: STAGING WITH OBJECTS ACROSS HETEROGENEOUS NETWORKS

In this section, I draw on the narrative to consider how objects are staged in translations from technology to product development. I focus on the performance of objects in enabling and coordinating translations, with an emphasis on how the deliberate circulation of objects by specific collective actors such as the top management, sales and TDP teams (un)intentionally (dis)aligned the networks into which the objects were assembled. To that end, I consider the roles played by four objects in four different *movements*, or intentional courses of action towards defined objectives.

Figure 1 illustrates four objects—the TRA, whitepaper, tuned self-alignment[47] and business case—that were chronologically staged in the four different movements. Each object is

[47] As an object, tuned self-alignment was the materialization of conceptualizations through which a specific functionality was achieved. A heterogeneous network including mathematical simulations supported its reliability, and all specifications for fabricating, controlling and assembling components into a prototype.

visualized as an object box containing elements comprising the object's network. These networks are not comprehensive. Drawing on methodological rules set by Latour (1987), I include elements from a 'network in action', considering only the observed performance of an element within a specific movement. When an object box includes a previous object among its network elements, I also include elements from the previous object box which were reopened in negotiations during the movement. For example, the whitepaper object box includes the TRA object as well as the preliminary business case, patents, working principles and steering characteristics which were part of its network and were explicitly renegotiated during the movement. If an element is not carried forward to the next object box, it implies that the element was (re)punctualized in the previous network.

Figure 1 shows network elements, together with the actor-networks involved in shaping them. Note that the actor-networks which shaped the elements changed across movements. Although the top management, TDP and sales teams were all involved in negotiations concerning the preliminary business case, patents, working principles and steering characteristics in the whitepaper object box, these elements were negotiated exclusively by the TDP team in the tuned self-alignment object box. Dashed arrows in the object boxes show the order in which elements were (de)stabilised in negotiations between movements. The four movements are shown as curved arrows above the object boxes. Note that each movement begins with an existing object and ends with a new object. The actor-network initiating a movement is shown at the start (left) of each arrow. The actor-network responsible for a movement's negotiations is shown at the centre of each arrow; for example, the TDP and sales teams coordinated movement between the TRA and whitepaper. The actor-network with a company mandate to define outcomes of a movement within the firm (the spokesperson) is shown at the end (right) of each arrow. Consider the first movement from TRA to whitepaper: the actor-network known as the sales team spoke for the whitepaper—a mandate rooted in the sales team representing the 'voice' of original equipment manufacturers (OEMs) within the confines of the firm. As such, the TDP, sales and top management teams are both actor-networks and spokespersons.

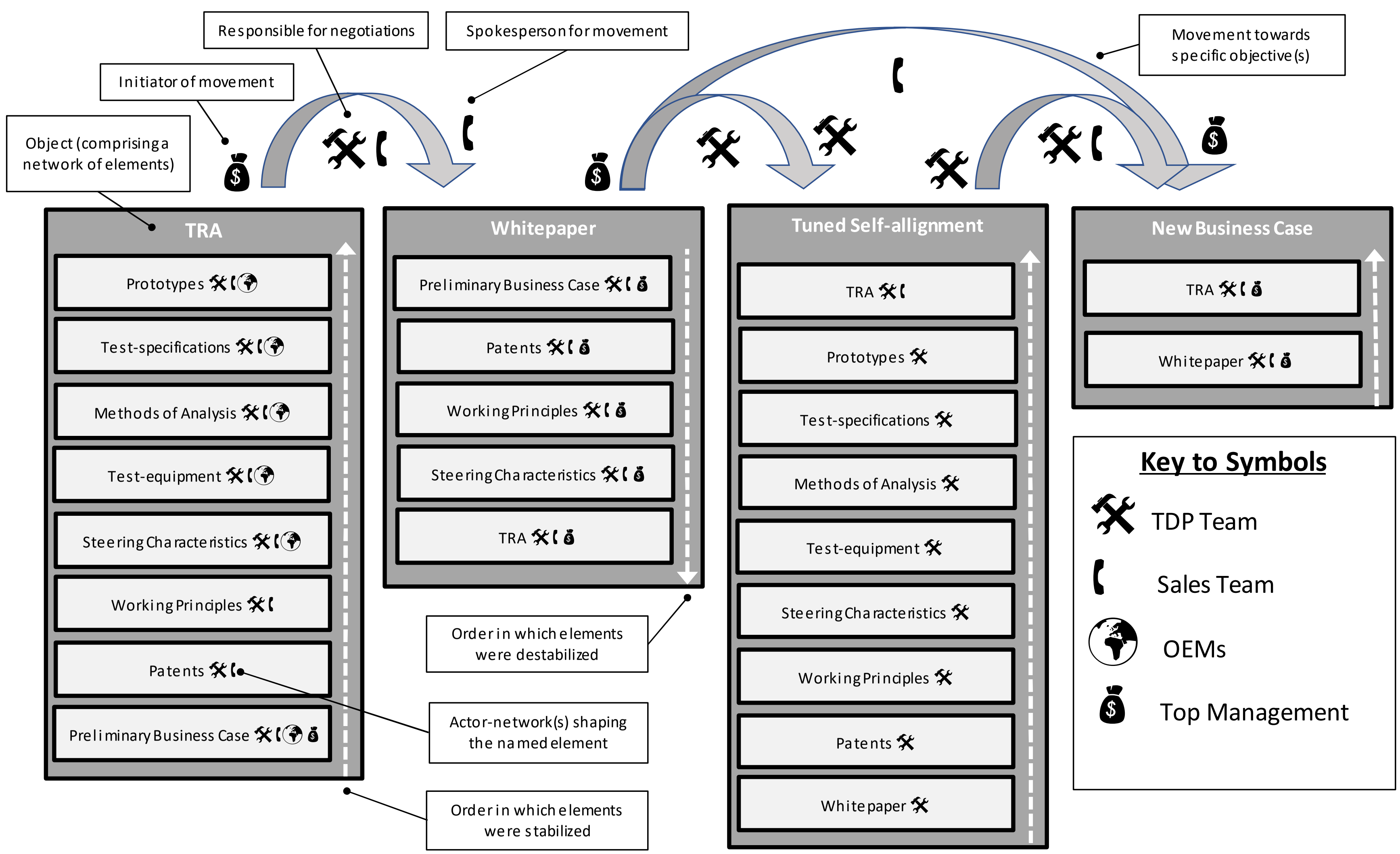

Figure 6: Four movements in the translation from TDP to PDP.

THE FIRST MOVEMENT: FROM THE TRA TO THE WHITEPAPER

The TRA was intended, and appeared, as a stable object for enabling the technology to move towards product-specific applications. Even so, the TRA was destabilised when encountering new demands engendered by the increased (albeit necessary) involvement of customers and managers in the transition from TDP to PDP. The initiative through which the preliminary business case was intended to be updated and validated (the whitepaper) faltered; paradoxically, the preliminary business case (a product of earlier customer interactions) was made obsolete by the very object commissioned to support it.

The TRA generated a ‘finalized number’ (Callon and Muniesa 2005; see also Bates and Clausen 2020) which could represent the foundational apparatus of the technology across contexts, without needing to bring the entire apparatus with it. This enabled a new attempt to commit customers to an implementation strategy, the whitepaper. Still, the foundational apparatus was itself undermined by translations of new customer demands that the attempt fostered. As customer requirements were redefined through interactions with the whitepaper, the functionality and reliability of the technology lost credibility with the top management team and the preliminary business case became obsolete. The first movement thus resonates with earlier STS observations on how seemingly mature inventions are destabilised in interaction with end-users (see Fleck 1988).

THE SECOND MOVEMENT: FROM THE WHITEPAPER TO THE NEW BUSINESS CASE

The second movement was instigated by the top management team in response to the destabilising effects of the first movement on the TRA network. It can be summarized as the TDP and sales teams’ engagement with top management to accommodate the new notions of functionality and reliability fostered by deeper engagement with OEMs. When presented with the whitepaper, the top management team issued a new mandate: ‘from now on, commercialization drives development’. This wording is interesting, as it illustrates different perspectives on translation, seen from the vantage points of PDP and TDP teams. In product development, network building ideally begins with specific (assumedly stable) customer perspectives. In technology development, network building begins with the functionality and reliability of inventions for specific (assumedly relevant) applications. The new business case had to accommodate both.

The top management team articulated a necessary and overarching objective: commercialization (per the whitepaper) would drive the technology towards the new business case. Still, a direct connection between the whitepaper and new business case was absent. The *means* by which the network elements of the TRA object could be re-stabilised (or superseded) to accommodate findings in the whitepaper were neither known nor defined. An *interim movement* between the whitepaper and new business case was necessary. The TDP's reconceptualization of 'self-alignment' would serve as the object through which the whitepaper and a new business case could be connected.

THE THIRD MOVEMENT: FROM THE WHITEPAPER TO TUNED SELF-ALIGNMENT

Considering the mandate that commercialization would drive development from that point forward, one may assume that activities preceding the whitepaper lacked a commercial focus. Such an assumption oversimplifies the development process. Activities did not lack a commercial focus; rather, the commercialization criteria that drove technology development were dynamic (see Fleck 1988).

As a milestone for moving industrial technologies through development phases, technology readiness was only relevant to *specific* end objectives (in this case, commercialization criteria). Although pilot customers actively supported the TDP and sales teams in defining the development process, unforeseen demands to implement the technology into new applications resituated the scope and sequence of a possible launch. The TRA network was destabilised because the whitepaper specified new commercialization criteria that differed from those guiding the technology's development.

To accommodate unexpected market expectations the TDP team needed to reconsider the working principles and steering characteristics driving the project. The discovery and recontextualization of a *functional flaw* ('poor self-alignment') provided a means to re-open these punctualized networks, address the destabilising aspects of new market demands, and finally stage 'tuned self-alignment' as a *functional feature.* This was possible because self-alignment was conceptualized in such a way that new validations could be reconfigured from existing elements; that is, the specifications, test setups, calculations and simulations supporting self-alignment were quasi-stable. Already designed and implemented by the TDP team to validate a variety of problematizations, network elements could be reassembled to validate new functional principles. Staging self-alignment in a new context (as tuneable) made concerns regarding the functionality and reliability of the technology tangible and malleable. This enabled the TDP and sales teams to negotiate new problematizations with familiar (albeit re-dimensioned and resituated) network elements. In other words, 'a certain kind of reality was [again] recognizable within the conditions of possibility' engendered by the whitepaper (Law 2009: 149).

THE FOURTH MOVEMENT: FROM TUNED SELF-ALIGNMENT TO THE NEW BUSINESS CASE

This movement is associated with restabilising the TRA and punctualizing tuned self-alignment. Although incomplete when this chapter was written, the fourth movement yields interesting insights into the process by which objects are staged towards punctualization. Consider Figure 1, where the TRA and the whitepaper are situated in the new business case object box as stable network elements. This reflects how the TDP and sales teams were successfully staging the TRA network to accommodate revised navigational considerations borne by the whitepaper. But notice that self-alignment does not appear as a separate entity in the new business case object box, even though it remained an important network element of the TRA object. Successfully staged by the TDP team as a response to dynamic commercialization criteria and leveraged to re-stabilise readiness, tuned self-alignment had been punctualized. Its interim role in the translation seemed to have been fulfilled.

Tuned self-alignment, which had been performed as part of a deliberate strategy ‘to create a durable network’ could now be ‘translated whole and “black boxed” into the [new] web’ where how the object works ‘is of little direct interest’ (Law 2009: 148). Although staging tuned self-alignment *facilitated* a necessary movement towards the new business case, the object will likely continue to lose visibility (and direct relevance) as the translation nears completion. Successfully staged, tuned self-alignment was resituated as one of many imperceptible critical technology elements comprising the network of steering characteristics, itself a punctualized element of the TRA network.

STAGING WITH OBJECTS AS AN ENGINEERING PRACTICE

Defined by the highly institutional process model employed by the company, the constitution of the transition space was largely a given. Working from assumptions permeating a preliminary business case, the TDP team was expected to establish a smooth transition from technology to product development. They were, from the outset, keen to avoid ‘throwing the concept over the wall’ between TDP and PDP.

This study illustrates a transition from invention to commercialization encompassing messy processes of interwoven translation, including a diverse array of shifting actors and objects that the orderly mechanistic processes depicted in mainstream management literature do not adequately capture. Focusing on the role of objects in staging these types of movements, I have conceptualized *staging with objects* to make sense of seemingly chaotic processes, while emphasizing the reciprocal nature of what actors do with objects as they are circulated. As such, the notion of staging with objects challenges the idea of a ‘great designer’ manipulating diverse elements to known ends (Law 2002). In the case presented here, actors rarely, if ever, managed to successfully stage objects single-handedly. Rather, translations were characterized as responding to possible means of action by identifying and connecting with objects already in circulation, always in cooperation with other actors and dependent on technical acumen. Movements from invention to commercialization resembled less a scripted play than improvisational theatre.

The configuration of the transition space was based on a translation of concerns voiced by actors (the TDP, PDP and sales managers, the vice president and president) who served as spokespeople, representing the perspectives of their networks to translate strategic challenges and opportunities in different ways. Although I was the primary actor responsible for staging the transition through the first movements (in my role as the TDP manager), managing the movement from TDP to PDP became a larger political concern as agency to initiate, negotiate and communicate the results of movements shifted between the TDP, sales and top management teams in unexpected ways (see Figure 1). This illustrates how the staging required to move a concept from TDP to PDP does not reside in a single actor, but becomes a matter of negotiation among shifting (f)actors. One implication of this, is the difficulty in identifying a single actor or network capable of managing the entire transition process. In the final movement, my role in making sense of the perspectives of the top management team, sales team and customers, and altering technological objects was taken over by the PDP manager; who also responded to what were often destabilizing actions in his attempts to stabilize an actor-network constituting a viable product concept. Tracing these efforts, staging implies numerous and different actions, including assembling and coordinating intersecting networks, constructing and/or assembling knowledge objects, and (re)circulating and (re)defining these objects through a dialogic process. The process described in the narrative exemplifies a successful, albeit meandering, orchestration of object creation/reframing and network translation.

Such an orchestration can hardly be seen as the simple outcome of an explicit and goal-directed staging process. Rather, it is an outcome of open, interactive processes spanning diverse actors and objects. A key finding is how shifts in staging efforts across organizational perspectives and competences were effectuated by the definition, development and circulation of intermediary objects oscillating between commissioning and mediating roles. Accordingly, competing concerns and strategies for how to stabilize or destabilize these objects becomes a key aspect in how movements from technology to product concepts and network translations are staged. As such, this translation from technological innovation to product concept cannot be adequately understood as the transition of a singular ‘product concept’ through or between presupposed situations. The objects considered here *all* performed as intermediary objects involved in the construction, circulation, (de)stabilization and eventual punctualization of an invention as it moved towards commercialization.

Surprisingly, the principle object involved in restabilising the TRA network in response to the whitepaper was borne by a functional *flaw* staged as a functional *feature.* Here, the deliberate redefinition of tuned self-alignment (through cross-disciplinary collaboration and reframed observations) served as a key translational move to reconfigure and eventually stabilize a product concept. This move re-established the TDP team as a key actor in the overall translation process and points at the importance of not punctualizing (or black boxing) technology concepts too early.

Moreover, attending to the capabilities of a cross-disciplinary project team to reassemble technological concepts during *ad hoc* movements between invention and commercialization seems of key importance. Whereas definitions of technology elements were rooted in assumptions from a preliminary (and later destabilized) business case, their functional conceptualizations were flexible enough to survive dis- and re-association. I hypothesize that the obscure, albeit permeating, role of the tuned self-alignment object, deep in the 'machine room' of the already punctualized network in which it was integrated, played a significant role in the staging efforts to turn an unsuccessful (destabilizing) translation into a successful (stabilizing) translation. The lesson seems to be that translation of the broader TDP network depended on deep technological knowledge accumulated in the TDP network, coupled with abilities to identify and reassemble an actor-network behind punctualized objects and to develop new conceptual objects for (re)circulation in dynamic contexts.

- In conclusion, I present the following points to help technology managers and engineers utilize staging with objects as an engineering practice:
- The agency to situate and define objects is a complex process of negotiation and does not reside in a single actor. Objects are reciprocally (de)stabilized by the effects of actors' changing positions as they navigate changing situations.
- Staging with objects requires increased attention to how objects perform across intentional (commissioning) and unpredictable (mediating) roles. This necessitates conscious reflection over how objects are accepted, contested and changed in interaction with different perspectives.
- Attention to processes of staging with objects can help technology managers and engineers articulate and accommodate fluid demands from top management teams who set overarching objectives, exercise control over resources, and provide mandates for action, but are otherwise not directly involved in solving technical issues in translations from invention to commercialization.
- Viewing 'commercialization criteria' as products of ongoing negotiations between diverse actor-networks can provide more effective strategies (*means of action*) than viewing these criteria as stable, punctualized entities that guide how a technology is developed.

REFERENCES

Bates, C. A., & Clausen, C. (2020), 'Engineering readiness: How the TRL figure of merit coordinates technology development', *Engineering Studies,* DOI: 10.1080/19378629.2020.1728282.

Callon, M. (1991), 'Techno-economic networks and irreversibility', in Law (ed.), *A sociology of monsters: Essays on power, technology, and domination*, Abingdon-on-Thames, UK: Routledge, pp. 277-303.

Clausen, C., & Yoshinaka, Y. (2009), 'The Role of Devices in Staging Front End Innovation', in *Proceedings of the First International Conference on Integration of Design, Engineering and Management for Innovation IDEMI09*, Porto: FEUP Faculty of Engineering and Management of the University of Porto, 1-8.

Cooper, R. G. (2008), 'Perspective: The Stage-Gate® idea-to-launch process—Update, what's new, and NexGen systems', *Journal of product innovation management*, **25** (3), 213-232.

Fleck, J. (1988), 'Innofusion or diffusation? The nature of technological development in robotics', *University of Edinburgh, Research Centre for Social Sciences*, **4**.

Florén, H., & Frishammar, J. (2012), 'From preliminary ideas to corroborated product definitions: Managing the front end of new product development', *California Management Review*, **54** (4), 20-43.

Latour, B., & Woolgar, S. (1979), *Laboratory life: The social construction of scientific facts,* Beverly Hills, USA: Sage.

Latour, B. (1987), *Science in action: How to follow scientists and engineers through society*, Cambridge, MA, USA: Harvard University Press.

Law, J. (1987), 'Technology and heterogeneous engineering: The case of Portuguese expansion', reprinted in Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (eds.) (2012), *The Social Construction of Technological Systems:*

New Directions in the Sociology and History of Technology, Anniversary Edition, Cambridge, MA, USA: The MIT Press, pp. 105-128

Law, J. (2009), 'Actor Network Theory and Material Semiotics', in Bryan S. Turner (ed.), *The New Blackwell Companion to Social Theory*, Hoboken, NJ, USA: Wiley-Blackwell Publishing, 141-158.

Mankins, J. C. (2009), 'Technology readiness assessments: A retrospective', *Acta Astronautica*, **65** (9-10), 1216-1223.

Markham, S. K., Ward, S. J., Aiman-Smith, L., & Kingon, A. I. (2010), 'The valley of death as context for role theory in product innovation', *Journal of Product Innovation Management*, **27** (3), 402-417.

Verworn, B., Herstatt, C., & Nagahira, A. (2008), 'The fuzzy front end of Japanese new product development projects: impact on success and differences between incremental and radical projects', *R&D Management*, **38** (1), 1-19.

Vinck, D. (2009), *Everyday Engineering: An Ethnography of Design and Innovation*, Cambridge: MIT Press.

Vinck, D. (2010), *The Sociology of Scientific Work*, Cheltenham, UK and Northampton, MA, USA: Edward Elgar Publishing.

Vinck, D. (2012), 'Accessing material culture by following intermediary objects', in Loshini Naidoo (ed.), *An Ethnography of Global Landscapes and Corridors*, London, UK: IntechOpen, pp. 89-108.

Vinck, D., Jeantet, A., & Laureillard, P. (1996), 'Objects and Other Intermediaries in the Sociotechnical Process of Product Design: an exploratory approach', *The role of design in the shaping of technology*, **5**, 297-320.

Appendix C. Staging Referential Alignment in Industrial-academic Collaboration

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Abstract

This auto-ethnographic study considers the transition from technology to product development in an industrial case led by the author. The chapter reflects on 'staging with objects' as a practice by which entities, defined as networks composed of humans and non-humans as well as material and immaterial objects, are assembled to perform in processes of translation. This notion of staging intends to increase understanding of how problematizations and qualifications concerning the suitability of an invention for product specific applications are negotiated across heterogenous networks. In contrast to mechanistic management perceptions, the chapter presents a a fresh perspective on the active use of objects in the practices of managers and engineers occupied with transitions from invention to commercialization. In conclusion, I present four points to help technology managers and engineers utilize staging with objects as an engineering practice.

Keywords: ANT; Auto-ethnography; Intermediary Objects, Staging, Technology Development, Translation

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INTRODUCTION

In this chapter, we investigate a collaboration led by the first author between tribological scientists and engineers from Luleå University of Technology (LTU) in Sweden and the Work Functions Division (WF) of the Danish owned Danfoss Power Solutions (DPS), a global leader in off-highway mobile hydraulics (Danfoss Group 2020, p. 7). The purpose is to describe and characterize micro-processes involved in the development of a new, environmentally-friendly non-petroleum lubricant technology within a petroleum lubricant-based industry. Our staging focus is on how WF and LTU negotiated test specifications to document wear effects on machine components run with the new lubricant. The collaboration was initiated by LTU under the assumption that replacing standard hydraulic fluids with the new non-petroleum lubricant would require cooperation with the mobile hydraulic industry. Because DPS is a major technology leader and brand within this industry, the tests performed by the manufacturer were important for demonstrating the functionality and reliability of the new environmentally-friendly lubricant.

Here, we explore how staging within the domain of technology development can be investigated and understood. Typically, scientific and industrial collaboration partners operate within different organizational and institutional settings and under different performance expectations (Juhl 2016). Although staging can involve many kinds of activities that produce new 'spaces' for opportunities within existing organizational frameworks, we direct our empirical focus specifically to a series of technology tests and how these can be understood in terms of staging. The tests were initially performed to demonstrate functional reliability for a new lubricant, but were later extended to generate deeper theoretical understandings of lubrication standards and attritional effects. Our framing of the term 'staging' therefore concerns the careful orchestration of technology tests and the collaborative environment necessary for its undertaking. In this space, we consider the test setup not only as a means through which staging was conducted, but also as an object of and the objective for the staging.

Our analytic intention is to conceptualize staging in relation to how the collaborative space is performed through and around the technology tests. Detailed descriptions of the work carried out before, during and after these tests, including the material agency of the tests themselves, are therefore instrumental to understanding the *what*, *how* and *why* of the staging activities. In short, it was the test setup that was staged through negotiations and interpretations around articulation of the technology tests. The 'why' is a bit more complicated, and requires situational analyses and questioning the performative nature of specific intentions behind the careful orchestration of the test setup. To conceptualize performances achieved through the technology tests, we adopt the perspective of 'innovation science', which denotes a 'domain of knowledge production . . . [wherein] academic scientists produce knowledge for commercial ends' (Juhl 2016, p. 136). Innovation science is inherently performative; 'in contrast to pure academic science that produces universal knowledge, innovation science produces knowledge that is particular to its intended application environment' (Juhl 2016, p. 137). Innovation science connects the relative universality of theoretical scientific knowledge with particular situated and technological conditions.

In this chapter, we examine how a distributed technology test setup was staged to produce coherent results that satisfied diverse organizational and institutional requirements in a knowledge exchange between the mobile hydraulic industry and the scientific field of tribology. To this end, we present a narrative describing how social, economic, organizational, technical and scientific elements were connected and made relevant to develop a test setup that could demonstrate the functionality and reliability of a new non-petroleum lubricant. An important finding is how standards were central to the collaboration's alignment of test parameters, interests and knowledge—particularly standards for petroleum lubricants, which shape the entire industry.

TECHNOLOGY TESTS, SCIENTIFIC EXPERIMENTS AND STANDARDS

To investigate these dynamics, we draw on analytic resources from ANT's semiotics and hybridity (Latour 1987, 1999), including Jasanoff's (2004) 'co-production' idiom, which is based on the understanding that normative and epistemic processes shape and constitute one another. To articulate the test setup's role as a coordinating object, we draw inspiration from Vinck's (2011, p. 25) idea of 'equipping intermediary objects': 'Through the process of equipping, new properties are conferred on the intermediary object and this contributes to the shaping of the design space and collective work'. Specifically, this chapter documents the process through which intermediary objects (mainly a test rig) were staged to progressively acquire properties of 'boundary objects' (Star and Griesemer 1989) and thus facilitate a many-to-many translation process of interessement. From this perspective, collaborating entrepreneurs were able to reduce local uncertainty while maintaining coordinated cooperation among allies through an 'indeterminate number of coherent sets of translations' (Star and Griesemer 1989, pp. 390–1).

By treating the development of the test setup as a case of innovation science, we analyse how the collaborative partners staged what we term 'referential alignment' between the standards and objects of the mobile hydraulic industry and the representations and computations of the scientific discipline of tribology. Referential alignment is a term that we develop to characterize the quality of referential relationships that enables knowledge artefacts and processes to refer back and forth between different material, organizational, local and temporal settings. Referential alignment is fundamental to enable, and thus stage knowledge exchanges between distinct epistemic cultures (such as between industry and academia). Latour (1999) developed the 'circulating reference' concept to explain the amplification of a message that manifests itself throughout cascades of translations of matter-sign vehicles in scientific practice. Still, Latour's empirical demonstration of circulating reference in Boa Vista remained within the confines of established field sciences and their practices. Whereas the empirical site was new and unique, the methods underwriting the scientists' translation of the forest into a field laboratory fits the description of 'ready-made science' (Latour 1987). In ready-made science, norms for interpretation and evidential requirements are already established and considered stable enough for other matters to form translations and be built upon them. In contrast, when we examine staging of referential alignment in technology tests between scientists and industrialists, the performance resembles 'science-in-the-making' (Latour 1987), wherein facts and machines are still 'under-determined' and shared norms for interpretation and evidence have yet to be established.

Although the present case does not fall squarely within the realms of 'ready-made science' or 'science-in-the-making', the theoretical significance is that all collaborators simultaneously were trying to establish *what* they required the test setup to produce, and *how* the tests could be designed to deliver these outcomes as a shared and coherent epistemic foundation upon which the collaboration could operate. While determining what exactly needed to be tested, collaborators engaged in a complementary process to establish organizational and institutional expectations of the tests. In addition to the tests' techno-scientific content, the tests' normative context was also subject to ongoing staging in order to establish the tests' institutional and organizational affiliations, purposes and the performance criteria by which the test results would be evaluated.

RESEARCH METHOD AND BACKGROUND

Our theoretical framework builds upon actor-network theory (ANT; Callon 1984; Latour 1987; Law 2009), which requires analyses to account for the agency of both human and non-human actors. This is especially important when considering spaces for technological development, where arrangements of test setups, industrial and scientific standards, and specialized measurement equipment all contribute to and condition the potential outcomes of processes of negotiation.

The first author led the collaboration in his role as Manager of Motor Engineering Technology (MMET) in WF. MMET played the role of 'auto-ethnographer', possessing 'prior knowledge of the people, their culture and language, as well as the ability to […] 'pass' as a native member' (Hayano 1979, p. 100) in the collaboration.

Shortly after the collaboration began, the MMET contacted the second author and extended an invitation to actively participate in the project, that they might draw on innovation science to benefit the collaborators' reflective praxis. The empirical material draws on both authors' direct participation in translating results across the collaborating organizations, as well as academic papers and simulation models by

WF, LTU or both, emails, test specifications, audio recordings of interactions, industrial brochures and standards, and ISO norms. All of these were discussed and (re)assessed with case participants prior to publication.

Methodologically, this chapter draws on ‘laboratory studies’ of ANT, which ‘take into account the organisational variables linked to the allocation of resources, communication structures and relations between organisational entities’ (Vinck 2010, p. 83). Viewing research as an enactment, insofar as ‘realities are enacted with the discovery that they are enacted differently in different places’ (Law 2009, p. 152), we draw on the notion of staging to describe and analyse how the constitution, configuration and transformation (Clausen and Yoshinaka 2009) of the actors and objects propagating the collaboration were (re)assembled in real time.

We present the notion of ‘staging in situ’ to sensitize towards translations that are enacted from within a commercialization collaboration by actors integral to the work by which both organizations subsist, as they (re)assemble objects in development processes while striving to retain and stabilize as much of their preceding work as possible. Although external consultants and/or researchers undeniably perform enactments within such collaborations, we consider staging in situ to be a skilled management practice different from that performed by researchers and consultants who are not embedded within the locally situated understanding of the objects they observe (and may or may not reciprocally manipulate).

Within such collaborations, objects underwrite the processes and goals they are situated to support (Vinck 2011). This is particularly true in scientific-industrial collaborations where principles of physics manifest through the results of experiments and tests. Although scientific experiments and technology tests both take place within controlled environments, experiments are performed to generate data to verify, challenge and build theory, whereas tests probe the functionality of technology and the usefulness of the models informing the particular design (Downer 2007). A significant consequence of this difference is that technology tests and scientific experiments are arranged to accommodate different targets. Tests typically refer to intended ‘real world’ applications of technology, and are organized to alleviate issues that reduce the ability of results to demonstrate a specific functionality or reliability under field conditions. Experiments are designed to produce results that fit modelling parameters so that the underlying theoretical models can be assessed (Sismondo 1999; Winsberg 1999). Consequently, scientific and industrial data productions can reflect oppositional referential requirements in situations where continued collaboration requires referential alignment. Consequently, industrial technology tests and scientific laboratory experiments must be coordinated if they are to support a shared and coherent knowledge production process.

Within such collaborations, actors do more than just situate and manipulate objects towards data production:

> The equipping of intermediary objects changes the status and ontological properties of these objects and contributes to the shaping of the design space and work collective. By equipment, we mean any element added to intermediary objects enabling them to be connected to conventional supports and spaces of circulation. (Vinck 2011, p.25)

The following narrative documents a process of *referential alignment* involving the transformation of an *intermediary object* into a *boundary object* which served as a center stage for coordinating various agendas and interests through a progression of *equipping work*.

A DISTRIBUTED TEST SETUP

Since 2005, WF had worked closely with LTU to understand and simulate mechanisms influencing orbital motor performance and durability. This work included bespoke kinetic and mechanical simulations, ad hoc optical measurements, analyses of finishing processes, and multiple co-authored publications (Furustig et al. 2015a, 2015b, 2016). With over 100 million SEK in direct funding from industry, LTU was the university in Sweden with the strongest track record for industrial collaboration, and was internationally recognized as an authority in two crucial knowledge areas for WF: modelling and simulation of contact mechanics, and tribology of lubricated interfaces. Building on this history of collaboration, a Chaired Professor in the Faculty of Engineering and Natural Sciences approached the first author in his role as MMET to request industrial support in order to benchmark a new sustainable, renewable, nontoxic, water-miscible replacement for the *de facto* standard hydraulic lubricant.

CONSTITUTING THE TEST SETUP

Together with associates from LTU, the Chaired Professor had recently established Sustainalube AB, a start-up company focused on developing, manufacturing and selling the lubricant. Sustainalube had already received Swedish public funding and prestigious innovation prizes, including Venture Cup Sweden and Swedebank Future Prize. Sustainalube had focused primarily on positioning the technology as a substitute for grease and chainsaw lubricants in the forestry industry, but was seeking to expand into new markets, particularly the mobile hydraulic market. This market places significant demands on hydraulic systems, with expectations for minimum maintenance and few breakdowns. Such demands pose two essential requirements: valid long-term stress-tests, and reliable data showing that the individual components comprising a hydraulic system can maintain high efficiencies over the entire component lifecycle, without adversely affecting the other components with which they interact.

The lubricant permeates all components in a hydraulic system and is the medium by which hydraulic energy is converted into mechanical energy. In mobile hydraulic systems, pumps, motors, proportional valves, steering units and transmissions typically draw fluid from a single reservoir. The same fluid is thereby commuted to propel or steer a vehicle, actuate cylinders or turn motors to generate work. Verifying the functionality and reliability of lubricants therefore requires a test setup that can circumscribe a wide range of applications and standards. Principle standards (for example, ISO 3448: 1992) classify lubricants according to viscosity grades, which indicate their compressibility and thermal expansion, two significant parameters for a hydraulic system's functionality and reliability. Other guidelines define lubricants according to their refinement or percentages of saturates and sulphur. Although these variants have significant effects on how equipment performs, the possibilities for interchangeability between these and non-petroleum lubricants are mostly unknown. This knowledge deficit has significant implications for guarantees between hydraulic machine manufacturers and their trade partners, thereby necessitating in situ testing and customized evaluations. To address these implications, Sustainalube needed to stage existing, albeit limited, industry-wide knowledge to validate its lubricant as a risk-free alternative to ISO 32 oil. LTU scholars were acknowledged experts in modelling theoretical effects of different tribological systems. Still, they required an industry representative to define and execute practical experiments to support these models—an arduous task for which WF was well-equipped.

Although DPS neither made nor sold lubricants, its products must accommodate conditions inherent to or engendered by them. Benchmarking effects of potential lubricants was therefore sensible. Moreover, 'sustainability' was a company wide aspiration and provided additional justification for entering the collaboration. In accordance with principles of the UN Global Compact Initiative[48], Danfoss Group (the primary concern under which DPS is included) had prepared a sustainability report every year since 2014 (Danfoss Group 2020). These reports highlighted how Danfoss conducted 'business responsibly and profitably, with a view to maximizing sustainable value creation for society' (Danfoss Group 2020: 2). Still, sustainable alternatives to ISO 32 remained largely non-existent. Additionally, environmentally-friendly bio-lubricants were associated with large carbon footprints, high levels of toxicity and poor compatibility with the rubber and plastic components dominating the industry. The collaboration provided a unique branding opportunity for WF to demonstrate commitments to sustainability.

[48] According to their website, the UN Global compact is 'A voluntary initiative based on CEO commitments to implement universal sustainability principles and to take steps to support UN goals' (https://www.unglobalcompact.org/about, retrieved 08 May 2020).

CONFIGURING THE TEST SETUP

To move forward, the Chaired Professor introduced the Sustainalube CTO to MMET. In subsequent meetings, they discussed how the interests of their organizations could be accommodated. Interests included: affirming WF's position as a sustainability leader, verifying the functionality and reliability of Sustainalube's lubricant for mobile hydraulics, preparing articles for publication in academic journals, and generating specialized knowledge across both organizations regarding the operation of lubricants in hydraulic systems. With preliminary interests established, the CTO was invited to WF to present his invention to the division's directors and senior managers. In preparation for this meeting, the MMET discussed the collaboration with the WF Motor Engineering Director. Drawing on correspondence with LTU, they formulated a statement for the meeting invitation that was rooted in notions of sustainability:

> To accommodate the hydraulic market's growing environmental and functional demands, researchers from LTU have designed a new prototype fluid with the benefits of water and the lubricating effects of oil. This lubricant is water miscible, nontoxic, made from renewable sources, has tuneable viscosity, and is incompressible, with good wear properties and excellent friction properties.

The WF Motor Engineering Director also allocated a Design Engineer, a Test Engineer, a Laboratory Technician and a 200-litre capacity test rig to the project for a 10-week period. Such test rigs were central to the company's technological development, where design or process changes underwent meticulous tests and evaluations in order to demonstrate their operational reliability and performance. This was also true for the WF-LTU collaboration, where the test rig was central to the production of empirical validations for the entire test setup. The test rig thus functioned as an 'obligatory passage point' (OPP; Callon 1984) from where and through which all other development activities transpired and were defined. Drawing on the dramaturgical metaphors of Chapter 2 in this book, the test rig became the 'centre stage' upon which the collaboration would be orchestrated.

Ideally, the collaboration needed a test setup that would validate the functional reliability of the non-petroleum lubricant for the entire market. To this end, the effects of the different lubricants on the volumetric and mechanical efficiencies of an orbital motor had to be documented. Knowing the effects of different lubricants on the types and magnitudes of measured wear on sub-components was also necessary. To accommodate these actions, the MMET and Design Engineer settled on a method described in their recently published paper (Bates et al. 2018). They would mechanically measure the motors' key components using specialized equipment at WF before and after testing. They would also analyse data from scanning electron microscopes (SEM) at both organizations to evaluate types of wear inherent to the different lubricants. Finally, they would incorporate lessons from another project with LTU, utilizing specialized optical measuring equipment to create 3D surface roughness topographies of the gear sets before and after testing according to a new ISO standard that LTU had been utilizing since its inception, but which WF was just beginning to utilize. All motor components were categorized and labelled according to mechanical measurement results before sending them to LTU for 3D surface measurements. Components were then returned to WF for assembly and tests, remeasured (or SEM analysed) and sent back to LTU. This made it possible to compare similar sets of components across the petroleum and non-petroleum lubricants. The test design's careful preparation was intended to ensure sufficient referencing between the mechanical conditions of the two test runs, so that differences between the lubricants used in each test run would be the only 'relevant variable' to which differences in the recorded wear could be referred. Whereas the construction of references is a well-known practice within scientific work (Latour 1999), we observed this phenomenon in the context of technology development, where references were constructed to align material conditions between two situations and ensure juxtaposability between the recorded results of each. The knowledge produced was not universal in its applicability. Rather, the construction of references between material test conditions was situationally conditioned to the specific circumstances of the test setup (including the lubricants) through which operational performance was compared.

The test setup thus functioned as an object through which tasks, interests, and knowledge were coordinated among partners. Whereas Callon's (1984) idea of translation is based on the establishment of an OPP through which agendas and interests are realigned in order to support one main agenda, the test setup articulated, connected and coordinated plural agendas and interests through its referential infrastructure. As such, the test setup's coordinating role aligned more with Star and Griesemer's (1987) boundary object concept; articulating translation at multiple levels and leaving room to adapt to local needs while concurrently maintaining a common identity.

Having established the test setup's expected deliverables, WF still needed a test specification compatible with the allocated test rig and timeframe. This was easier said than done. The test rig had restricted flow and pressure capacities. Furthermore, conducting two test runs in an area where components could be significantly worn within the timeframe required testing motors at the limits of their intermittent specifications. This further reduced test possibilities to three displacement sizes (the volume of oil displaced by the gear set, in cubic centimetres) spanning two different motor types.

Once the motors were selected, the team needed to ensure that the two sets of motors were comparable as described above. Comparability was central for creating referential alignment between the two planned test runs and ensuring that magnitudes and positions of wear could be correlated across the two lubricants.

Benchmark testing could now be initiated.

TRANSFORMING THE TEST SETUP

> The MMET, Design Engineer and Test Engineer were at LTU to discuss the results of their first test iterations and measurements with the Chaired Professor and CTO.
>
> MMET: The last time I was in this room was for cake, when Furustig got his doctorate.[49]
>
> Chaired Professor: Oh! Can WF still use his wear model? No one here has touched it since.
>
> MMET: Yes. Mostly the Design Engineer. The CTO asked him about it yesterday. We can use it to calculate the gear set's entrainment speeds at different flows, pressures and viscosities, so the CTO can molecularly tune the oil to solve our problem.

Their problem was complex. Two sets of motors had been measured and remeasured after tests with ISO 32 and Sustainalube lubricants. Unfortunately, Sustainalube gear sets showed extreme attrition, including adhesive, abrasive and multiparticle wear. Two gear sets had seized. Furthermore, the 10-week allocation for the test rig had expired. The CTO went to the whiteboard, speaking while writing equations:

> The oil film is too thin at EHL [elastohydrodynamic lubrication] contacts. Dowson and Higginson [1966] formulas look like this. The Design Engineer can give me entrainment speed and contact forces from the Furustig model. I also need ISO 32 properties. I can get the rest from ball-on-disc tests: friction, precise wear coefficients […] Then I can tune the lubricant.

Ball-on-disc tests are an established scientific standard within tribology. Although test rigs are costly, and rare specialized knowledge is required to correlate results with in situ component tests, ball-on-disc results are the best approximation to theoretical values upon which practical simulations are based.

> MMET [pacing]: Chaired Professor, we have 3D surface characteristics from the CTO and the specs for your discs. If we machine and supply

[49] Dialogues were translated from Swedish or Danish, edited for clarity and approved by those cited.

> representative discs and the CTO performs the tests and analyses the data, then I'm sure we can keep the test rig with Sustainalube oil, at least for the year. Their results contribute to future modelling capabilities [...] But how does LTU get paid?
>
> CTO [interjecting]: Sustainalube's funding application included ball-on-disc. We have the means to pay LTU.
>
> Test Engineer: If WF needs the friction and wear coefficients, the lab should support this. Not just for the LTU know-how—that's huge—but also our focus on sustainability.
>
> MMET: Correct. And don't underestimate the academic articles this will generate. These support our position as industry leader. We should be driving the industry.
>
> CTO: What if I tune the oil to a different viscosity, where it can outperform ISO 32?

Albeit ambitious, the request was problematic. Orbital motors were a single component in a system comprising multiple components connected to the same tank. The industry standard was 35 cSt viscosity, roughly equivalent to ISO 32 at 40 degrees Celsius.

> MMET: No. Sorry. Mobile hydraulic is a conservative industry geared to 35 cSt. It's the only way in.
>
> Test Engineer: Look I'm new. But why 35? If it's better at 14 or 40 or whatever, customers will want it? Our motors are run hard. Steering units last forever. Motors are where the wear is?
>
> Chaired Professor: Yes, but ISO 32 is the culmination of, what, 100 years of ad hoc development? It wasn't chosen; it evolved. It won't take 100 years for something to replace it, but it's the criterion [...] Sustainalube will pay for ball-on-disc. So yes, the CTO can tune the lubricant. But is there a test area within 35 cSt that could help move the bar?
>
> MMET: Re-dimensioning our tests and lubricant to a different application area? [...] Maybe. But we'll need a new benchmark.

Although a comparison between the two test runs produced empirical data on differences in operational properties between the two lubricants, the data were not directly commensurable with theoretical parameters such as those used in the Furstig model. Dowson and Higgison formulas are based on parameters that are not directly measurable in situ. To establish these theoretical parameters for the lubricant, a dedicated laboratory ball-on-disc setup was required to control and remove as many variables as possible and ensure that output data was commensurable with the theoretical parameters the CTO needed to re-tune the new lubricant. WF tests had established an *industrial context* in which the new lubricant was made comparable with the standard ISO 32 oil. Adding LTU ball-on-disc equipment to the mix intended to engender a *scientific context* in which the lubricants and the WF-fabricated discs could function as industrial objects, whose friction properties could become theoretically knowable. By creating a coherent infrastructure of references, the facilitation of these industrial and scientific tests would establish referential alignment among industry standards, ISO 32 oil, the new lubricant, and the tribological models serving as a relevant explanatory resource. It was precisely this referential alignment (across industrial settings, academic fields, theoretical models, new and old lubricants and standards) that established conditions for the exchange of knowledge and know-how between industry and academia. In turn, this referential alignment was conditional for both the theoretical tuning of the new lubricant *and* its industrial reliability.

Back in Denmark, the MMET met with the BU Engineering Director and the Laboratory Manager. His message was clear. Although promising, the non-petroleum lubricant was not fully developed: simulations needed to be made, ball-on-disc tests needed to be completed. The test-specification also needed to be changed to accommodate an ideal application. Sustainability was not low-hanging fruit.

The Laboratory Manager was supportive. The collaboration advanced condition monitoring competencies which supported future lab investments. Although the BU Engineering Director agreed that co-authored papers between WF and LTU would support WF's status as a sustainability leader, he was chiefly concerned with the capacity of ball-on-disc tests to improve WF simulation capabilities. Weighing the costs of testing against new theoretical and practical knowledge and branding potential, the BU Engineering Director, Laboratory Manager and MMET agreed that Sustainalube benchmark tests should continue. The panel would be made available for an additional 16 weeks.

DISCUSSION: STAGING REFERENTIAL ALIGNMENT

The WF contribution was to facilitate production of new knowledge regarding the lubricant's performance within a controlled industrial test environment that emulated 'real-world' conditions. The WF test lab granted the material conditions for establishing referential alignment between industrial objects, operational practices and ISO standards. In return, LTU provided the new lubricant technology and state-of-the-art scientific testing equipment, with data output conforming to established scientific standards within tribology. This constellation of hybrid academic and industrial data production with mutual reference to the same test setup was essential to stage a reference-borne knowledge infrastructure through which members of the hydraulic industry and tribology experts were able to exchange knowledge, know-how and success criteria. Collaboratory success in this case can be seen as depending on the ability to facilitate referential alignment and thereby (re)situate knowledges, methodologies and material objects across diverse organizational and institutional requirements.

Staging sustainability was a central objective for the collaboration and initially served as the qualifying success criterion towards which the fulfilment of different visons and resources were aligned. Although supporting its reputation as a sustainability leader had originally piqued WF's interest in the collaboration and helped constitute the network, sustainability benefits were insufficient to sustain the network in the face of unexpected test results. Fortunately for the collaboration, the initial objective of demonstrating WF's commitments to sustainability could be re-staged as supporting new opportunities presented by ball-on-disc tests. Whereas ball-on-disc tests were deemed necessary *objects* for Sustainalube to tune its lubricant, they became an *objective* for WF, providing them with entirely new opportunities to understand gear set mechanics and tribological interfaces and to expand modelling capabilities. Still, Sustainalube's and LTU's objectives remained unchanged: Sustainalube needed to provide a functional and reliable alternative for ISO 32 oil, and LTU wished to maintain and improve its position as a world leader in industrial research collaboration.

This was not true for the Sustainalube lubricant, which could only be staged (connected and made relevant) for and by the test setup through a one-to-many OPP—namely, functional reliability as per ISO lubrication standards. Unfortunately for Sustainalube AB, these standards proved to be specific in their application to petroleum-based lubricants for which and by which they had been derived. The molecularly situated nature of the standards severely limited the conditions of possibility by which the functionality and reliability of the new lubricant could be validated. This resonates with Hardstone et al. (2006, p. 70-1), who proposed that:

> Where the scale and scope of activity become too large for direct scrutiny, simple forms of communitarian trust may come in to play based upon presumptions of reciprocity, broadly shared norms and established repertoires of behaviour and rooted in experience of repeated performance.

Just as oil is the medium that permeats a hydraulic system, the ISO 32 oil standard permeats the entire hydraulic industry, where its repeated performance has produced normative expectations that idealize its characteristics as the dominant technology in a market 'too large for direct scrutiny'. As pointed out by the Chaired Professor, these characteristics were neither designed nor chosen, but rather incrementally shaped and refined over the last century through use within the simultaneously emerging industries to which it served as a common reference point. The OPP by which the new lubricant could be (re)assembled into the test setup had the effect of supporting ISO 32 dominance.

To complicate matters further, the initial function of the WF test rig was that of an intermediary object still oscillating between translating goals into results and instigating action and negotiation (Vinck 2011). It was the constituting and configuring work that 'equipped' the test setup into possessing more substantial boundary object characteristics as it gradually became more integral to the operations of the entire collaboration.

The addition of ball-on-disc to the test setup would make it possible to identify and quantify the parameters by which the new lubricant could be tuned and made relevant, providing new means to accommodate demands defined by the ISO lubrication standards. Perhaps more importantly, ball-on-disc tests could provide theoretical values by which WF could expand and improve their practical simulations, as well as provide LTU with fundamental understandings of tribological interactions which could be connected to practical experiments. As such, ball-on-disc was not just assembled into the test setup in pursuit of centralized goals. Rather, it became a goal unto itself. Whereas other collaboration targets shaped preliminary and final ideas about what the test setup should perform—namely, augmenting WF's status as a sustainability leader, supporting LTU's status as a top industrial collaboration partner, and providing commercialization opportunities for Sustainalube—incorproating ball-on-disc into the test setup was both a *means* to accomplishing these targets and a separate *end* for WF, providing access to theoretical coefficients for future simulations.

CONCLUSION

Our primary focus in this chapter has been to provide an empirically substantiated theorization of the 'what, how and why' of staging in a case involving technology tests and the associated industrial-academic hybrid production of knowledge. We have invoked the staging metaphor to sensitize readers to the ongoing work that practitioners put into constituting, configuring and transforming diverse material and epistemic conditions in order to create and maintain a referential infrastructure across different situated settings. An important part of this type of staging is the negotiation and coordination of normative expectations and performance criteria in order to define a shared space for the different collaborators.

As a key object, the test setup was critical in the early connection of partners around 'common performance criteria'; paradoxically, the results of the test setup required the network (in the form of partners, resources and the setup itself) to be staged around a new problem definition and new objectives. Here, the possible means of tuning a new non-petroleum lubricant were dependent upon industry-wide standards geared towards maintaining the superiority of petroleum-based lubricants. Consequently, the collaboration had to be reconstituted, reconfigured and retransformed around a new theoretical problem the scientists excelled at solving, rather than the initial and more practical demonstration problem for which the industry partner had been approached for assistance. Within this process, maintaining referential alignment across the different organizational settings meant that knowledge built by the collaborators had to be broken down and replaced with questions whose answers required a new agenda. As the principle subject of the staging considered here, the test setup became more than a means for demonstrating the functionality and reliability of the new environmentally-friendly lubricant. It also became a dialogic tool for negotiating established notions of validity.

Finally, this chapter documents the upstream constitution and configuration of an intermediary object to perform as a boundary object (that is, a referential infrastructure) as its comparability and commensurability were shaped across diverse stakeholders. Here, an intermediary object (the test rig) was initially staged as an OPP to support translation and alignment. Through this process of constituting the preliminary establishment of involved interests and configuring, through new knowledge production and its translation into reference construction and alignment of material conditions, the test setup represents a way to transform intermediary objects into boundary objects, and to ensure juxtaposability between the results of each, in supplement to the process documented by Vinck (2011). Conceptualizing this as a process of referential alignment could be the subject of future work.

REFERENCES

Bates, C., Broe-Richter, H., Bendlin, C., & Ennemark, P. (2020), 'Case study: The effect of an amorphous hydrogenated carbon-coated gear-wheel on a hydraulic orbital motor's efficiency over time', *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, **234** (3), 320–333.

Callon, M. (1984), 'Some elements of a sociology of translation: domestication of the scallops and the fishermen of St Brieuc Bay', *The Sociological Review*, **32** (1_suppl), 196-233.

Clausen, C., & Yoshinaka, Y. (2009), 'The Role of Devices in Staging Front End Innovation', in *Proceedings of the First International Conference on Integration of Design, Engineering and Management for Innovation IDEMI09*, Porto: FEUP Faculty of Engineering and Management of the University of Porto, 1-8.

Danfoss Group (2020), *The Sustainability Report 2019*. Nordborg, Denmark: Danfoss Group.

Downer, J. (2007), 'When the chick hits the fan: representativeness and reproducibility in technological tests', *Social Studies of Science*, **37** (1), 7-26.

Dowson D. & Higginson G. (1966), *Elasto-hydrodynamic lubrication: the fundamentals of roller and gear lubrication*. Oxford, UK: Pergamon Press.

Furustig, J., Almqvist, A., Bates, C. A., Ennemark, P., & Larsson, R. (2015a), 'A two scale mixed lubrication wearing-in model, applied to hydraulic motors', *Tribology International*, **90**, 248-256.

Furustig, J., Larsson, R., Almqvist, A., Bates, C. A., & Ennemark, P. (2015b), 'A wear model for EHL contacts in gerotor type hydraulic motors', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, **229** (2), 254-264.

Furustig, J., Almqvist, A., Pelcastre, L., Bates, C. A., Ennemark, P., & Larsson, R. (2016), 'A strategy for wear analysis using numerical and experimental tools', applied to orbital type hydraulic motors. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, **230** (12), 2086-2097.

Hardstone, G., d'Adderio, L., & Williams, R. (2006), 'Standardization, trust and dependability', in Karen Clarke, Gillian Hardstone, Mark Rouncefield, Ian Sommerville (eds), *Trust in technology: A socio-technical perspective*, Dordrecht, Germany: Springer, 69-103.

Jasanoff, S. (Ed.). (2004), *States of knowledge: the co-production of science and the social order*, Abingdon-on-Thames, UK: Routledge.

Joakim Juhl (2016), 'Innovation science: between models and machines', *Engineering Studies*, **8** (2), 116-139.

Latour, B. (1987), *Science in action: How to follow scientists and engineers through society*, Cambridge, USA: Harvard University press.

Latour, B. (1999) Circulating Reference: Sampling the Soil in the Amazon Forest. In *Pandora's Hope: Essays on the Reality of Science Studies,* 24-79. Cambridge, USA: Harvard University Press, 24-79.

Law, J. (2009), 'Actor Network Theory and Material Semiotics', in Bryan S. Turner (ed), *The New Blackwell Companion to Social Theory*, Hoboken, USA: Wiley-Blackwell Publishing, 141-158.

Sismondo, S. (1999), 'Models, Simulations, and Their Objects', *Science in Context,* **12** (2), 247-260.

Star, S. L., & Griesemer, J. R. (1989), 'Institutional ecology translations and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39', *Social studies of Science*, **19** (3), 387-420.

Vinck, D. (2010), *The Sociology of Scientific Work*, Cheltenham, UK and Northampton, MA, USA: Edward Elgar Publishing.

Vinck, D. (2011), 'Taking intermediary objects and equipping work into account in the study of engineering practices', *Engineering Studies,* **3** (1), 25-44.

Winsberg, E. (1999), 'Sanctioning Models: The Epistemology of Simulation', *Science in Context,* **12** (2), 275-292.

Appendix D. Positioning Patents to Perform Coordinative Action in Industrial Technology Development

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Abstract

From an STS perspective technology development is seen as an outcome of a translational process, including numerous coordinative actions. Although STS scholarship has criticized management tools like process models and figures of merit for taking technology and new ideas for granted and black boxing these into key figures of how they are expected to perform, the focus remain, by and large on the these management tools (in decision-making contexts) and their role as objects in processes of translation.

By diving into an actual engineering process and following the objects and decisions involved in how a technology is being shaped, this paper submits that other objects, such as a series of patent applications, play hitherto unrecognized and coordinative roles in the development process. Accordingly, this article concludes that the management of technological development does not solely rely on mainstream management tools and how they are translated (however unexpectedly), but that technology development practice seems to be dependent on how other overlooked objects, such as industrial patents, are positioned to perform coordinative action in ways that challenge taken for granted assumptions about how these objects are utilized.

Keywords: Engineering Practice; Patents; STS; Technology Development

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INTRODUCTION

This article is concerned with the role of *overlooked* objects in industrial innovation management, where developing novel technologies for product specific applications involves numerous objects with varying degrees of visibility. Of these objects, the most evident are specifically designed to support and guide decision-making processes. These include process models and figures of merit (FOM)[50], as well as specifications and standards serving at inter-/organizational and inter-/national levels. Other objects, like patents, trademarks and non-disclosure agreements, are meant to appropriate or protect the commercial rights of organizations developing technologies. A key characteristic of both these groups of objects is that their inclusion in a development space is usually a given – they are not necessarily *chosen* by the technology managers and engineers comprising a development team, but condition principle aspects of their work arrangements. A third group of objects encompasses those brought into a development space in order to meet or accommodate conditions defined or revealed by objects from the previous groups. Such objects include measurement, test and manufacturing equipment, specifications, prototypes, mathematical models, and methods of analysis defined by technology managers and engineers *for* and *within* the development space.

Management literature is mainly concerned with the recipes and operations of the first group but does not reflect the complex sociotechnical practices – what Vinck terms ‘everyday engineering’ (2009) – that have been considered in STS scholarship on such objects (see Bates and Clausen 2020; Christiansen and Varnes 2007; Hansen and Clausen 2017). Moreover, process models and FOM ‘black box’ technology development – reducing a complex process to easily communicable and generalizable *milestones*, *levels* or *ratings* – where technology managers and engineers require objects which can unlock the ‘engine room’ of a technology for design and innovation. According to Vinck (2014: k), “engineering is above all a work of coordination, linked to practice-related contingencies and to the distribution of expertise among multiple actors”. The question so arises, **how is technology and innovation coordinated when the key concepts applied in industry are seemingly insufficient for the tasks at hand?**

The case described here is rooted in a series of hydraulic patent applications and how these were positioned to coordinate action in a *technology development project* (TDP). This is interesting because it is a rare (perhaps the first) empirical analysis of patents performing to *manage* actions associated with developing and validating the functionality and reliability of a novel technology in an industrial setting. Drawing

[50] In the engineering and natural sciences, a figure of merit, “usually presents itself as a single number that reflects the status or the performance of any particular system under particular specified conditions” (Borg et al. 2012: 1).

on a case from Danfoss Power Solutions (DPS)[51], this article provides new insights into the detailed practices by which technology managers and engineers reciprocally position and manipulate objects to ‘circumscribe agencies’, ‘organize encounters’ and ‘establish conventions’ (see Callon and Muniesa 2005) in processes of technology development. From a practical perspective, this implies that technology development teams must *circumscribe* intentions of the development space and the objects necessary for achieving these intentions, *organize encounters* between objects by defining their associations, and *establish conventions* by which these associations will be aligned and made relevant for one another in a new mobile composite entity that can leave the development space without taking its entire network with it. In line with STS thinking, this article does not consider these actions as sequential phases of a linear process. Rather, these terms are understood as mutually shaping and recurring moments within a complex process of *translation* “that relates, defines, and orders objects, human and otherwise” (Law 2009: 145) – *across or despite* the intentions of a development space. Williams and Edge (1996: 866) posit that when “technology does not emerge from the unfolding of a predetermined logic or a single determinant, then innovation is a *garden of forking paths*”. I employ Callon and Muniesa’s (2005: 1232) three moments of ‘qualculation’ – a notion of calculation that includes judgement and focuses on “arrangements that allow calculation (either quantitative or qualitative) and those that make it [im]possible” – as a means of analyzing how these forking paths are navigated in processes of technology development. Although Callon and Muniesa (2005) advance these three moments (i.e. *circumscribing agencies, organizing encounters* and *establishing conventions*) for analyzing processes of ‘economic network stabilization’, Bates and Clausen (2020) have also demonstrated their utility in analyzing how *technological* networks are stabilized.

STS scholarship has criticized management tools (like process models and FOM) for taking technology and new ideas for granted and black boxing these into key figures of how they are expected to perform. Vagn Jensen et (2018) propose that the dominant perspective built into process models is one of management control, focusing more on selecting and (de-)accelerating ideas than on how innovations are encouraged. Moreover, the widespread assumption within TRL literature that basic science is a mainstay of linear progress at higher levels of innovation is also disputed (see Narayanamurti and Odumosu 2016, and Szajnfarber and Weigel 2013). Finally, *practices of the processes* by which such artefacts are circulated are often overlooked (Clausen and Yoshinaka 2009; Hansen and Clausen 2017) and the normative approaches adopted by the management sciences are often more interested in *developing* these types of management tools than in *studying how* such tools perform (Callon 2002).

A comparable criticism is also present in this article, which takes root in empirical material from a technology development project (TDP) led by the author to argue that

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[51] Danfoss Power Solutions is a global leader in the off-highway mobile hydraulic industry. https://www.danfoss.com/en/about-danfoss/our-businesses/power-solutions. Retrieved 27 July, 2020.

such decision-making devices do not necessarily support the *translations* upon which future decisions will rest and that other objects are inevitably positioned and manipulated *en route* to these finalized decisions. In a similar vein, Christiansen and Varnes (2007) consider the use of 'gate and portfolio management systems' in industrial technology development to demonstrate that there is a myriad of other 'micro-decisions' that must be made to accommodate the decisions a development space is intended to support, and propose an STS inspired 'network process perspective' to replace the 'linear management perspective' that dominates much of 'innovation management thinking'. To this end, Christiansen and Varnes elegantly demonstrate how the decision-making meetings that supposedly *distinguish* these process models are ultimately displaced by 'mandatory templates' serving as 'boundary objects' (Star and Griesemer 1989) or 'obligatory passage points' (OPP, Callon 1984). According to Christiansen and Varnes, such templates provide access to the meetings while *de facto* defining formal requirements for the projects these meetings are intended to support. For a technology manager like myself, this is certainly a useful finding. Still, Christiansen and Varnes' attention remains within the confines of the process model as a 'decision-making device', describing movements between the *decision-making gates*, *portfolio meetings* and *mandatory objects* of which these devices are comprised. In a comparable endeavor to illuminate the workings of a widespread, assumedly mechanistic and linear management tool through STS theory, Bates and Clausen (2020) consider how the 'technology readiness level' (TRL) figure of merit performed as a 'calculative device' (Callon and Muniesa 2005) in the hands of skilled practitioners – to circumscribe and organize calculative agencies, and establish rules and conventions for accountability – in a technology development project. By viewing TRL as *more* than a scale for communicating established facts, Bates and Clausen demonstrate how TRL serves *to produce and (de)stabilize facts* through processes of (re-)negotiation. A key finding from this work is that a company sanctioned template defining the TRL device was de- and re-stabilized to perform as a 'provoking, dialogic instrument', which reciprocally shaped the topics and findings of assessment meetings and was ultimately leveraged to acquire necessary resources. Whereas Christiansen and Varnes (2007), and Bates and Clausen (2020) focus on mainstream management devices and how they are deployed by skilled practitioners to support decision-making, this article shifts focus from management devices to other technical objects in a TDP network – considering how practitioners position and manipulate such objects (in this case a series of patent applications) towards *achieving* the characteristics upon which finalized decisions rest.

Still, STS research within this subject area is by and large focused on process models and FOMs (in a decision-making context) while pointing to their role as objects in processes of translation. By providing an STS perspective on how *patents* are positioned to coordinate action in industrial practice, this article moves focus *from* these mainstream management tools to demonstrate that there are a variety of other objects playing unacknowledged roles in the practice of coordinating technology development. Following this series of patents provides a more realistic picture of industrial technology development than the decision-making focus carried by these management tools and our STS understanding of them.

Extant STS scholarship on patents is directed more towards their effects on or within economic markets, or how commercial appropriation is tied to scientific research. Maguire (2018) considers how tensions between 'prototyping' and 'patents' served to limit the possible futures of early Danish aeronautics. Conceptualizing prototyping as "what happens to sociality when the craft and agency of objects are approached in a particular way", Maguire concludes that by prioritizing "the delimiting work of patenting", the Danish pilot, inventor and entrepreneur J.C.H Ellehammer actually decoupled his own "anticipatory work of prototyping" from a market helped engender (and strived to dominate) in such a way that *alignment* across the worlds of invention and commercial appropriation became impossible to sustain (ibid: 26-27). In earlier patent studies, Mackenzie et al. (1987; 1990) investigate the effects of economic interests and patenting on scientific production in the biomedical field of antibody research, noting patents do not necessarily provide 'technical self-sufficiency' for their academic or industrial creators – patents perform as one of multiple *technology resources* across both domains – but nevertheless appropriate information previously perceived to be in the public domain. Viewing patents as *texts*, Bowker (1992) is concerned with how patents can be viewed as 'boundary making devices' which can be (re-)positioned and (re-)interpreted to defend and shape emerging or changing areas of a market towards the patent holders' present or future dominance. In contrast to these other scholars, this article considers the relationship between patents and a commercial market only *implicitly* (via customer demands to a new technology). Rather, this is a story of a series of patents being positioned to perform outside of their supposed *raison d'être* – in order to coordinate actions associated with developing and validating the functionality and reliability of a novel technology.

The following section introduces concepts and theoretical perspectives used in the analysis and the research method, before presenting an empirical narrative that follows a series of patent applications as they are positioned by their inventors to effectively manage actions purposed with materializing and validating a new steering technology for the off-highway mobile market. A discussion then ensues, on *how* these patent applications performed to circumscribe agencies, organize encounters and establish conventions across dynamic exigencies. The conclusion places supposed essentialities of process models and figures of merit in a more realistic context than that of their advocates, suggesting that other objects are necessarily positioned and manipulated by skilled practitioners towards *achieving* the characteristics upon which finalized decisions rest.

STS CONCEPTS AND PERCEPTIONS EMPLOYED IN THIS INDUSTRIAL STUDY

This article employs theoretical perspectives from STS – and actor-network theory (ANT) in particular – which posit that *associations* (aka, *webs*, *weaves* or *networks*) are: ‘performative’, they *do* things; ‘fragile’, associations must be maintained, sometimes at the cost of other associations; and above all ‘heterogeneous’, social and material elements overlap, influence each other, and assemble as pieces of a greater whole – *or they do not.* (Law 2009). To study these associations, Law (2011 [1986]: 37) provides the notion of ‘heterogeneity’, or more specifically ‘heterogeneous engineering’, as a foundation for considering engagements where “various *different types* of bits and pieces [are juxtaposed] in order to exercise control”. I submit technology development projects are examples of such *engagements*. Within these projects, a diversity of *actors* (buyers and sellers, laboratories and technicians, R&D departments and engineers) and *objects* (business cases, measurement equipment, test specifications, prototypes and process models) are assembled into complex networks which must move intact across space and time or be reassembled following disassembly – despite or through *other* networks of which their elements are a part.

To address this heterogeneity, Star and Griesemer (1989) present the notion of ‘boundary objects’ (BO) – designed to consider “the *flow* of objects and concepts through [a] network of participating allies and social worlds” while focusing on understanding processes of management occurring *across* these allies and worlds (ibid: 389.) Boundary objects are interesting because they must concurrently adapt to local contexts, constraints and exigencies of the parties employing them while maintaining a common identity across multiple sites. As an example, consider the ISO standard (1219-1:2012) which defines the symbols employed in the patent of figure 3. ISO-1219 allows technologies to be defined, communicated and understood across diverse intentions and broad contexts within the hydraulic community, making it possible for its members to work independently and still exchange information, (if they so choose) in a format applicable to other members of the community. This illustrates how boundary objects “are a sort of arrangement that allow different groups to work together without consensus” (Star 2010: 602).

Vinck’s ‘intermediary objects’ concept (2011, 2012, 2014; Vinck et al. 1996) is designed towards similar ends. A principle difference between these concepts is the intentionally weaker conceptualization of intermediary objects (Vinck 2012). While a BO implies forms of *stability*, maintaining *common identities* across sites, an intermediary object (IO) is *also* applicable within a variety of *other* situations (ibid: 94). Unlike BO, which rest at the *intersections* of social worlds, IO are ‘on the move’ – their *identities* can change (Vinck 2011, 2012). According to Vinck (2011) identities of IO change through a process of ‘equipping’ – a notion for describing how the sociotechnical possibilities and intentions of collective work are reciprocally shaped, *in tack with* properties being conferred on the IO. In a previous case study from the same division, Bates and Juhl (2020, forthcoming) draw on the notions of *BO*, *IO* and *equipping* to document the transformation of an IO into a BO acting as a 'center stage' for the development of a sustainable lubricant. This article presents a similar line of reasoning considering different technologies.

RESEARCH METHOD

Empirical material stems from a *technology development project* (TDP) which I led at DPS, where I have worked with the development of new component, material, product and process technologies associated with the design, verification and production of hydraulic motors and steering units since 2005. In selecting and analyzing the empirical material, I draw on the method of 'following objects and actors' (Vinck 2011, 2012, 2014; Vinck et al. 1996). Vinck (2012: 95) suggests that, because an object "constitutes a trace and a mark of its authors and their relations", following an object can provide information "about its authors and the sociotechnical conditions of their activity, about the paths they follow and the contingencies that arise". Initially I followed specific objects sanctioned by the company to support decision-making processes: A 'TRL Assessment Tool' and a Cooper inspired 'NPD Process Model' as these were employed by my team. Although these objects had made significant contributions at other intersections of the project, they were less visible in the case considered here. At this juncture, decision-making tools seemed only peripherally involved in how actions necessary for *achieving* the functionality and reliability of the technology were being managed, *despite* these objects being well-integrated into the formalized processes upon which finalized decisions rest. I thus revisited empirical material to review audio-recordings, correspondence, notes, photographs, simulations and standards. By following Latour's (1987) *rules of method* – only including objects from a 'network in action', and the *observed* performance of these objects within the technology development network – I pinpointed a series of patent applications at the *center of action* within the junction described. STS concepts of *boundary objects*, *intermediary objects* and *equipping* allowed me to analyze and make sense of these complex interactions. A narrative of how the patent applications were positioned and performed follows here.

NARRATIVE: POSITIONING PATENTS TO MANAGE ACTION

The industrial project was rooted in two patent applications submitted in 2015 (Ennemark et al. 2016a, 2016b) that describe novel principles for safe and comfortable hydrostatic steering at unprecedented speeds. Six months later, the division's top management established a TDP and I was asked to lead the project and its associated activities to prove and develop the principles. Within the division, TDP are meant to mature and develop novel technologies so they might later be implemented into *product development projects* (PDP) according to the 'project milestones' defined in a company sanctioned NPD process model. Although TRL assessments are an important part of PDP, where TRL demonstrate a technology's *readiness* and support movements between specific milestones, neither the TRL nor NPD process model into which it fed seemed significant in mobilizing the resources and actions moving the project forward. To help understand these mobilizations, I briefly introduce the technology upon which the TDP was focused.

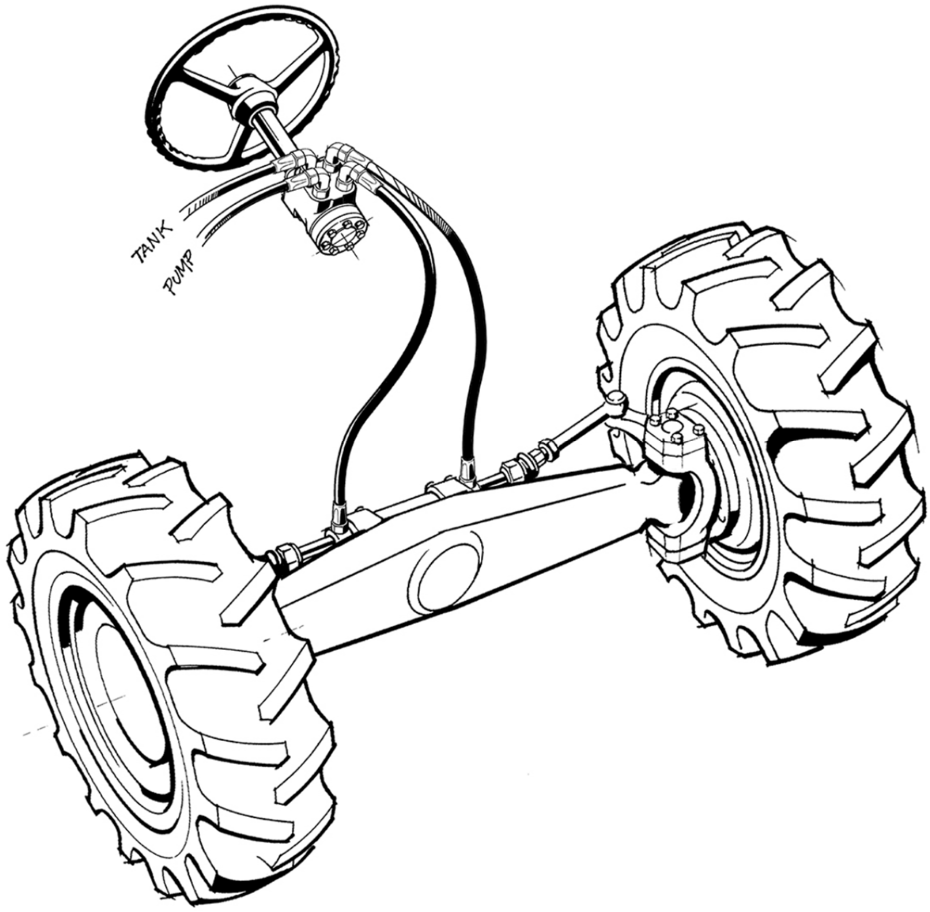

Figure 7: Hydraulic steering system comprising hydraulic pipes and hoses, a steering unit and steering cylinder(s), where the steering unit meters oil to the cylinder(s) via the steering wheel interface (Danfoss A/S 2017: 7).

A fully hydraulic steering system provides power so that the wheels of a vehicle (often a tractor) can be turned with reduced effort. Figure 1 illustrates such a system, with a hydraulic steering unit shown under the steering wheel. Figure 2 illustrates the principle components of a hydrostatic steering unit, which is designed to deliver specific magnitudes of oil to the hydraulic cylinder in direct correlation with partial or full revolutions of a steering wheel (A.) turned by a driver. Simply put, delivery is achieved through an orbital gear-set (B.) that is volumetrically (C.) and mechanically connected to a system of precisely dimensioned orifices (D.). These are positioned on an inner-spool (E.) and an outer-sleeve (F.), and open and close as they rotate in synchronization with the steering wheel. A hydrostatic steering unit is a highly compact and complex system of valves and channels controlling precise movements (*commutation*) of hydraulic fluid. By improving the stability and response time of this complex system, the patent applications of Ennemark et al. would enable safe and comfortable hydraulic steering at higher speeds than those presently available in the off-highway mobile market.

Ideally, a hydraulic patent incorporates standardized symbols to circumscribe a finite

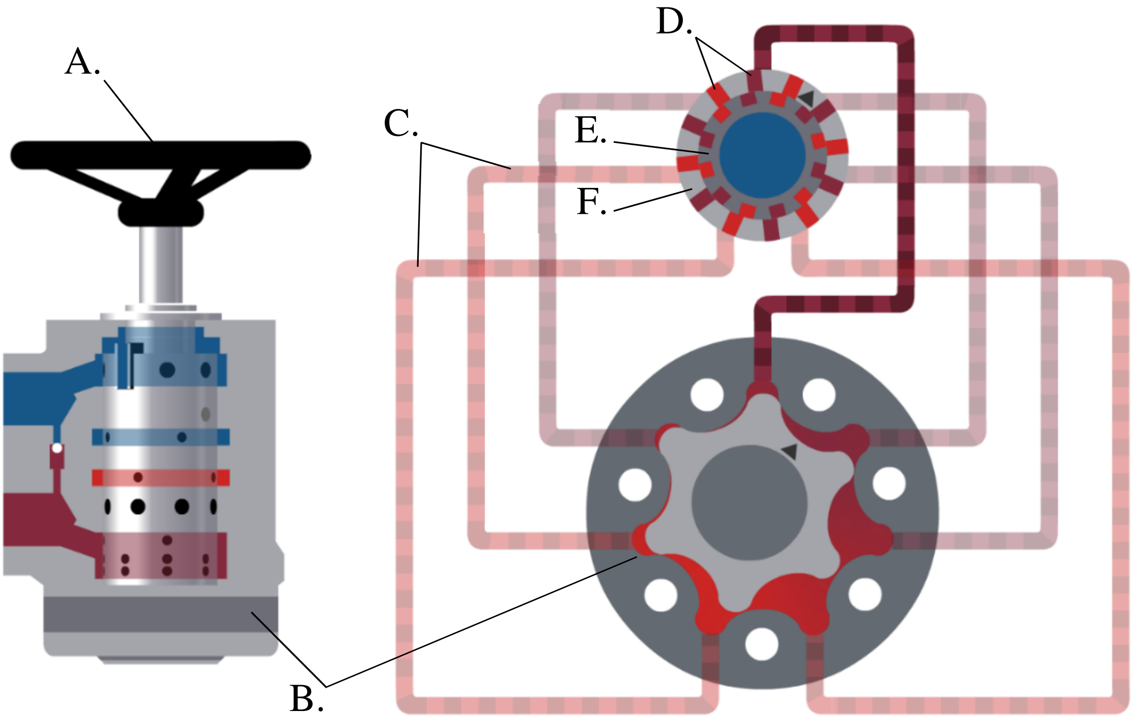

Figure 8: Working principle of a hydrostatic steering unit (Danfoss A/S 2019).

and specific order of functions, that innumerable functional realizations might be commercially appropriated. Hydraulic diagrams like the one shown in figure 3 are a principle element of a hydraulic patent – serving as a guideline for how these (appropriated) associations can be practically manifested. The diagram is dimensioned according to *Comité Européen des Transmissions Oléohydrauliques et Pneumatique* (CETOP) standards. The steering unit's order of functions are demarcated by the stippled square. The order of functions necessary to achieve safe and comfortable high-speed steering are defined by a sum of symbols (mostly describing different *valves*) connected by *channels* through which hydraulic fluid (*oil*) flows. The steering unit is pressurized with oil from a pressure source (the *hydrostatic pump*), shown outside of the stippled lines on the left of side the diagram, via an *inlet port* – this port is colored red on the left side of figure 2. The pump draws oil from a *tank*, which is shown outside of the stippled lines at the bottom of the diagram in figure 3. Oil is recirculated to the tank via an *outlet port* – this port is colored blue on the left side of figure 2. Finally, *hydraulic cylinders* are actuated by pressurized oil metered through the steering unit via the gear-set, valves and channels of figure 2. The hydraulic cylinders which turn the wheels of a vehicle are shown outside of the stippled lines, on the right side of the diagram in figure 3. It is important to note that the patent of figure 3 is not concerned with *how* any of these functions are achieved (i.e. their *design*). The patent *only* specifies precise functions and their associations (i.e. *a finite and specific order of functions*). While figure 2 demonstrates one way to manifest the patent (probably the *best* way regarding cost and efficacy), there are infinitely many other ways that the functions and associations can be achieved. This is what is meant by 'innumerable functional realizations'. *Sans* altruism, the patent is intentionally *fluid* – "entangled, in terms of both its performance and its nature, in a variety of worlds", it can maintain an *instable identity* without losing its *agency* (deLaet and Mol 2000: 227). This is illustrated in the following (absurd) vignette.

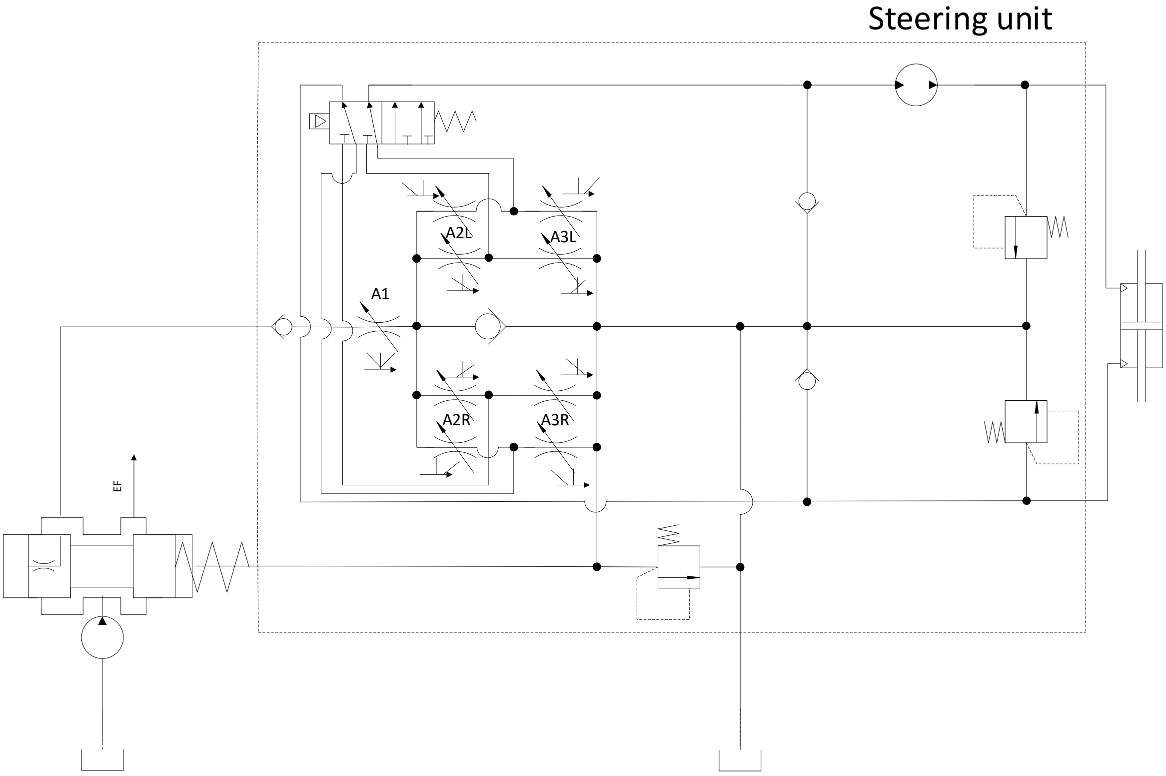

Figure 9: CETOP diagram from a patent for a safe and comfortable high-speed steering unit (Frederiksen et al. 2018: 8).

Assume a Storm P. type[52] replaces the system's *pressure source*, *hydraulic lubricant* and *tank* with an *elephant* trained to suck *champagne* out of a perpetually full *kiddie-pool* and spray the champagne into the inlet port of the steering unit through its trunk at high pressure. The patent would remain intact. Assume a *more rational* engineer, then optimizes the size or shapes of specific valves to accommodate the tribological properties of champagne – commuting fluid to these valves via precise lengths of

[52] Storm P. (Robert Storm Petersen, 1882-1949) was an autodidact Danish multimedia artist and philosopher famous for illustrations of absurd inventions and bizarre means of transport (Jernewicz 2005). His nearest international counterpart is probably the American multimedia artist, inventor and engineer Rube Goldberg (1883-1970).

garden-hose instead of machined channels opened and closed by the rotation of components inside of the steering unit. The patent would *probably* remain intact, insofar the *order* and *types* of functions remain the same, qua definitions of standardized symbols, and providing that no functions or channels are added or subtracted. It is this *finite and specific order* of functions, not their *design*, *efficacy* or *robustness*, which enable and appropriate *innumerable functional realizations.* Consequently, *maturing* the novel steering principle would also include *defining* other (ideally all) feasible combinations of functions for *application relevant* variants – that these might also be commercially appropriated. The CETOP diagram in figure 3 is a product of this work and one of three diagrams included in the patent it supports (itself one of nine patents in the series of patent applications considered here).

At this juncture, the TDP Team had submitted eight patent applications and the patent in figure 3 was still unfinished. The team had recently received an infusion of resources, in form of specialists and equipment upgrades, through which another application variant had attained higher *readiness* (see Bates and Clausen 2020). Concurrently, a large *original equipment manufacturer* (OEM) had been shown a preliminary CETOP diagram of a steering unit with figure 3's functionality and inquired into its readiness. Such early, though limited, OEM involvement in development is common and desirable within the off-highway mobile industry. Although sometimes destabilizing, such involvement directs development activities towards market needs or OEM vehicle architectures still in the pipeline (see Bates 2020, forthcoming). Hypothetically, the new variant would adapt the steering behavior of a vehicle to different on-road and off-road conditions, by (de)activating the two sets of Wheatstone bridges in figure 3 (these are also highlighted by the blue and green ovals in figure 4). Proving this hypothesis, within the time-constraints offered by the OEM would not be easy. A specific order of functions was *assumedly* in place, but a design for its manifestation was not. Validating the functionality of the new variant (V9, *for patent variant nine*, hereafter) required prototypes and tests targeting micro-performance within the *specific series of functions*, as well as verifying the *efficacy* of these components as *system outputs.* To these ends, the TDP Team organized two one-hour meetings with the PDP Team who would eventually take over the technology and the Technical Sales Team (also engineers) who had met with the OEM. During these meetings, participants would develop a course for moving forward with V9 that was not immediately visible or attended to in the management tools through which the development group was *assumedly* coordinating action. Meeting activities included sketching on whiteboards, passing around steering unit components, viewing CAD models, forecasted sales figures, engineering reports and simulations on a pull-down projection screen, and considering preliminary findings from other prototype variants. The first meeting opened with the System Simulation Specialist (SSS) sketching a CETOP diagram that was a precursor to V9 (figure 3) on a whiteboard. The second meeting opened with the division's Director of Technology (DT) sketching a similar order of functions as those drawn earlier by SSS. As DT was finishing the sketch, the PDP Manager chuckled and said, "The TDP Team knows this concept by heart".

"Yes", I replied, "It's a subject of our weekly patent meeting […] We promised [Senior Patent Consultant] to have an application ready in a few weeks". The Mechanical Hardware Specialist (MHS) interjected, "Wait. I have this digitally. Let me print copies". After receiving the prints, the participants silently read them. DT spoke first and quietly, "What if we take a blank for [propriety] housing, machine it as possible, and make two sets of spool-sleeve sets to accommodate the rest? One set functioning as the on-road variant, which we already proved, and one set functioning as the off-road variant". The group looked speculative. DT continued, "By matching differing orifices to the same commutation channels, we can prove the two Wheatstone bridges and measure their efficiencies in the same setup, viewing them separately, without the switch". SSS responded first, "We test the bridges independently keeping everything else stable. That would work". As the others began speaking, MHS placed his laptop on the table, projecting CETOP diagrams from two patent applications, Bates et al. (2018 – V1, hereafter) and Arbjerg et al. (2018 – V2, hereafter) onto the same screen. These patents showed the two functions of the double Wheatstone singularly, in simpler arrangements. MHS then pointed to the sketch on the whiteboard stating, "Here are our comparisons".[53] Over the next 6 weeks, these and other CETOP diagrams guided, supported and challenged negotiations to define a 'viable path forward'. The negotiations fostered new problematizations, mostly related to measuring the functionality of a *steering unit* and simulating the *internal functions* of the same. In short, *performance* of specific internal functions was not directly measurable. This is due a combination of components rotating under application, stringent component clearances (specified in micrometers), and high internal pressures (exceeding 200 bar). The sum of these associations made measurement at the point of *component function* impossible. 'Functionality' at the micro-level could only be *simulated* and *compared* to *measured* outputs at the macro-level. Moreover, *functionality* and *reliability* of the technology are defined by the applications into which it will be integrated. Proof of concepts must function within exigencies of the OEM's system-architectures – often defined in (significantly more complex) CETOP diagrams.

The sum of work arrangements derived to address these challenges are visualized in figure 4. The TDP Team designed interchangeable prototypes for different areas of application, drawing from V1 type variants for on-road functionality and V2 types for off-road functionality according to possibilities demarcated by V9 (illustrated by the patent in the upper-left corner of figure 4). The functionality of these designs was then simulated (in the upper-right corner of figure 4). The designs were then optimized according to simulations of the intended functions of the patent. When satisfactory results were achieved prototypes could be made. These prototypes were sent to laboratory tests (in the lower-right corner of figure 4) to measure the designs' functionality and efficacy. Test results were then fed back into simulations to ensure *specified functions* were performing as expected (the double-sided vertical arrows on the right of figure 4). Finally, test-track measurements of the prototypes (In the lower-left corner of figure 4) would demonstrate the designs' performance *in situ*, where this

[53] Dialogues were edited for clarity and brevity and translated from Danish by the author.

data was compared with laboratory tests (the double-sided horizontal arrows at the bottom of figure 4) and fed back into simulation models. These actions were repeated until correlations between the *measured* steering unit performance and *simulations* of CETOP diagrams' specific order of functions were deemed valid for specific system-architectures according to the patent (in the upper-right corner of figure 4). Upon completion, the Sales Team informed the OEM that a proof of concept was validated, providing them with interim performance results. The development process also laid bare early assumptions regarding the *finite* and *specific* order of functions defining the steering unit, allowing the TDP Team to optimize the V9 concept and develop two additional diagrams for inclusion in the patent. In the following section, I discuss how completed and interim patent applications performed to circumscribe agencies, organize encounters and establish conventions within this development process.

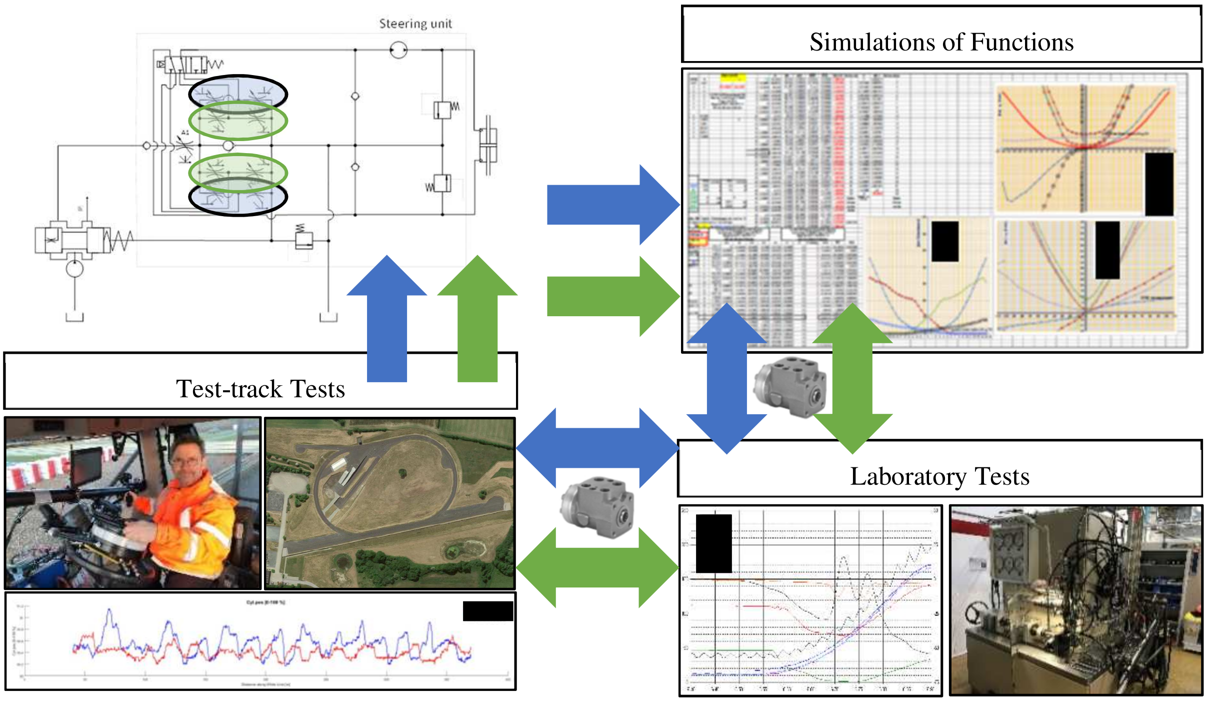

Figure 10: Illustration of coordinative actions to prove functionality and efficacy across work arrangements. The colored arrows represent two different designs, as these relate to the highlighted Wheatstone bridges in the CETOP diagram from the V9 patent at the top left of the figure. A steering unit placed between arrows indicates prototypes were involved in exchanges between the actions at either end of the arrows.

DISCUSSION: MANAGING COMPLEXITY IN TECHNOLOGY DEVELOPMENT

In the preceding narrative, specific actions supporting development were instigated in interaction with an OEM. To this end, work in progress – initially aimed at maturing the *functional principle*s of a *product variant* for a wider market – was expanded to accommodate the specific needs of a potential customer. In the off-highway mobile industry, these types of work arrangements are complicated by the fact that functional principles are not always customized for specific applications. Steering units must function 'out of the box' in an assortment of partially standardized system-architectures. The functional principles of product variants are therefore designed to perform across a variety of applications in diverse contexts. From this perspective, the technology managers and engineers of the *development group* (comprising the TDP, PDP and Sales Teams) can be seen as 'designing for a community'. According to Bowker and Star (1998: 231), designers of such community systems must simultaneously build for multiple *social worlds*[54]. In addition to the different associations within the development group, these social worlds included the vehicle applications towards which the product variant was being designed (e.g. earth movers, implement carriers, industrial tractors, rotary tillers, etc.) and the unique system-architectures spanning these applications – as voiced through interactions with the OEM and Sales Team.

Put simply, the development group needed to create and equate a proof of concept with a product variant in a 'hybrid entity' (the *product-variant-cum-proof-of-concept*) that could perform as a *boundary object* – initially for the TDP, PDP and Sales Teams, later for the OEM, and finally for the off-highway mobile market. Star (2010: 604) characterizes a BO "as a set of work arrangements that are at once material and processual". The *process* by which the proof of concept and product variant were equated is an example of such an arrangement. By design, the product-variant-cum-proof-of-concept was created and situated to accommodate the different functions of the development group and the OEM. This would ultimately allow the parties to adapt the product variant to their own local contexts, constraints and exigencies *without* destabilizing its common identity across the parties. Performing as a BO, the product-variant-cum-proof-of-concept would ultimately support the TDP Team in completing an interim patent application and developing a stable principle for broad application in a diverse market. For the PDP Team, the BO would provide a proven principle around which they could later design a product fulfilling supplementary demands for

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[54] Star's work promotes a pragmatist view of social worlds, defined as, "groups of activity having neither a clear border nor a formal and stable organization […] built up through the relation between social interactions generated by the primary activity and a suitable definition of reality" (Vinck 2012: 93).

marketability and manufacturability. For the Sales Team and OEM, the BO would eventually provide demonstrable compatibility with unique, partially standardized system-architectures, as well as measured and simulated data through which system compatibility could be scrutinized across system configurations. *Equipping* the product variant with a proof of concept would thereby allow it to effectively serve as a BO around which hydraulic steering systems could be designed, simulated and tested across the various needs of diverse social worlds without any of them needing to cooperate formally. In the following, I discuss how the product-variant-cum-proof-of-concept was successfully developed and positioned at these intersections of 'use and interpretation' through interaction with patent applications.

According to Vinck (2011: 25) "*equipping work* is the collective activity that involves agreeing about the features to be added to intermediary objects so that they can be enrolled in the space of exchange between actors". Drawing on this perspective, *conceptualizations* of the product variant's order of functions needed to materialize in a *tangible* proof of concept that could demonstrate its *functionality* and *efficacy* within a specific system-architecture while maintaining *relevancy* across the diverse system-architectures of the larger market. This was accomplished through planned interactions between designs, a simulation program, prototypes, laboratory tests and test-track tests, and the CETOP diagrams which defined precisely *how* such a steering unit could be manifested (see figure 4). With inspiration from Bowker and Star (1998), I submit that the *standardized* symbols which circumscribed the *finite and specific orders of functions* in the completed and interim patent applications were deployed in a context of 'making things work together' before being positioned to serve as the 'agreed-upon rules' by which work arrangements defining the equipping process were manifested.

The narrative describes a new conceptualization of a 'product variant' for a novel steering technology. Defined by a patent application dimensioned according to industrial norms (ISO, CETOP), the conceptualization had migrated between the OEM, and the Sales, PDP and TDP Teams and was eventually 'returned' to the development group by the OEM, with requests for a deeper understanding of its functionality and efficacy. Lacking tangible means by which this functionality could be demonstrated, the conceptualization became a *mediating object* – facilitating the integration of different viewpoints (see Vinck 2011). At this juncture the conceptualization was still *too* 'plastic'. Its 'interpretive flexibility' was insufficiently bounded. Achieving adaptability *between* contexts required that the product variant could maintain a different level of coherence *across* the diverse intentions of these contexts. To this end, specific features of functionality and efficacy were added to the conceptualization's identity. *The conceptualization was equipped*. According to Vinck (2012), this type of equipping is concerned with the way information is exchanged and retained within webs of associations. Figure 4 illustrates an intentional process of de- and re-stabilization as knowledge is generated across different associations. Here, iterations between work arrangements were repeated (not always with desired or intended effects), until the designed, simulated or measured behaviors of any single arrangement could be correlated with the behaviors of other arrangements.

This article asks, how technology and innovation are coordinated when the key concepts applied in industry are seemingly insufficient for the tasks at hand. The three moments of a 'calculative device' provide a possible answer. According to Callon and Muniesa (2005: 1231), *circumscription* is a process through which "a finite number of entities are moved, arranged and ordered in a single space". Interestingly, the process of demarcating, arranging and ordering in the case was coordinated through *previously* circumscribed entities. Already from the first meetings between the TDP Sales and PDP Teams, it seemed obvious for the participants that the completed and interim patent applications would shape their work arrangements, and the *finite and specific orders of functions* delineated by the standardized symbols defining these applications clearly served as the foundation upon which negotiations of functionality and efficacy took place. Because these *orders of functions* were able to move uninhibited between contexts without losing any of their meaning, the patents could perform as the lens through which knowledge being exchanged was deemed relevant at its point of application. By positioning the patent applications to circumscribe their work arrangements, the development group, was constructing something akin to a calculative device for producing a new entity: the *product-variant-cum-proof-of-concept boundary object* that would ultimately leave the calculative space and circulate elsewhere.

The development group's planned interactions between the narrative's different work arrangements – their 'organized encounters' – were more subtle. Although the orders of functions defining the conceptualization were fully constrained, their possible *design manifestations* were virtually unbounded (see the elephant example above) if not always viable. Three general constraints seemed to guide the development group's notions of *viability*: a) design manifestations were rooted in the *basic working principle* of a hydrostatic steering unit – see figure 2; b) supplementary demands for *marketability* and *manufacturability* needed to be met, and; c) *compatibility* with the unique and partially standardized system-architectures of the off-highway mobile market should be demonstrated – see figure 4. Here again, it was the *finite and specific order of functions* of the patent applications which served as the intersection where these *independent* constraints were brought together and made *interdependent* – and through which the product-variant-cum-proof-of-concept was ultimately assembled. The iterative process employed by the development group seemingly supports the findings of Vinck et al. (1996: 303), who discourage against considering an object's exchanges as "simple continuation[s] of previous[ly] stabilized relations". By repeatedly de- and re-stabilizing knowledge at the intersections of the work arrangements of figure 4, the development group was able to engender a product-variant-cum-proof-of-concept which seemed to achieve coherence *across* these arrangements. This is comparable, if not equivalent to what Callon and Muniesa (2005: 1238) describe as, "allow[ing] rich and varied relations between the entities thus selected, so that the space of possible classifications and reclassifications is largely open". Still, the product-variant-cum-proof-of-concept needed to maintain coherence across *more* than the work arrangements of the development space – its findings needed to travel to the OEM intact – without bringing the entire validation apparatus with it.

Once coherence is achieved, it must be maintained. Objects unable to achieve or maintain coherence are either disassociated into the composite elements of their associations or risk being transformed at every intersection, eventually losing their recognizability and applicability across the social worlds they were intend to serve (see Law 2009, 2011 [1986]; Star 2010; Star and Griesemer 1989; Vinck 2011, 2012, 2014; Vinck et al. 1996). In the case considered here, this required that the development group specify *how* the functionality and efficacy of the product-variant-cum-proof-of-concept would be *measured, assessed* and *manipulated* in interaction with the *finite and specific order of functions* of the patent application that it was designed to replicate – in ways that allowed these procedures to maintain relevance and applicability across contexts within the diversity of social worlds defining the market. For the product-variant-cum-proof-of-concept to perform as a boundary object, its outputs – be these thousands of recorded test-points for a specific parameter in a single spreadsheet, a Computer Aided Engineering simulation or a simple graph – would need to be implementable into the work arrangements of the OEM in ways that could be made sense of when they returned to the development group in new formats. Although this resonates with how Callon and Muniesa (2005: 1238) define the third moment, *establishment of conventions*, as "formaliz[ing] procedures and algorithms likely to multiply the possible hierarchies and classifications between […] entities", it is rather difficult to analytically *separate* these actions from those of the second moment. The decision to develop two different sets of spool-sleeve sets and test them in the same housing was certainly a procedure for establishing conventions. But it was *also* a means of organizing encounters between a patent's specific order of functions in a way that these functions could be made *calculable.* This reciprocity between the second and third moments was also apparent at the intersections of work arrangements where the prototypes where placed (see figure 4). *Organizing encounters* between the simulations, laboratory and test-track tests required that the *conventions* for treating these interactions were also in place. Here again, meeting these criteria was seemingly made easier (if not wholly possible) through the finite and specific orders of functions defined in the patent applications – which allowed them to develop a sort of non-linear template (i.e. a *calculative device*) through which the TDP, PDP and Sales Teams could develop the technology. A key-takeaway seems to be that the stability of the *orders of functions* in the patent applications provided the development group with a practical foothold through which they could *tolerate* uncertainty within the various work arrangements. This uncertainty is evident in how coordinative actions were designed to repeatedly challenge the stability of the composite elements by which functionality and efficacy were achieved (qua the working principles of figure 2) across a variety of contexts (qua figure 4), until these elements were ultimately made applicable and relevant for the vehicle architectures of a key customer.

CONCLUSION

This article ‘follows objects’ through an industrial case, utilizing STS perspectives on objects and heterogeneity to understand how a series of patents were positioned by their inventors to manage action in a technology development project. Although other STS scholars have criticized how mainstream management tools (like process models and figures of merit) perform to black box technology development according to a variety of taken for granted assumptions, the dominant focus of these scholars remains *on these management tools* and how they perform in processes of translation. With outset in a series of patent applications, the article moves focus from *how* mainstream management tools *perform* to demonstrate that *other* objects can be positioned to coordinate action in processes of technology development. To this end, empirical material was analyzed using the three moments of Callon and Muniesa’s *calculative device* to understand how completed and interim patent applications performed to *circumscribe agencies, organize encounters* and *establish conventions* within the development process. Here, the stability of the ‘finite and specific orders of functions’ in the patent applications seemed to provide the development group with a practical foothold through which they could tolerate uncertainty within their work arrangements. The stability of these *composite elements* also provided the basis for developing a sort of *calculative device* through which the development group could create and equate a proof of concept with a product variant in a ‘hybrid entity’ (the *product-variant-cum-proof-of-concept*) that could perform as a boundary object – initially for the TDP, PDP and Sales Teams, and later for a large OEM whose technical demands could be equated with those off-highway mobile market. A key takeaway seems to be that *because* these *orders of functions* could move uninhibited between contexts without losing any of their meaning, they could also be positioned to define both the *inputs* and *outputs* of the work arrangements through which the product-variant-cum-proof-of-concept was manifested. The stability of these orders of functions thus enabled the development group to intentionally de- and re-stabilize knowledge about the *functionality* and *efficacy* of the developing technology at the *intersections* of different work arrangements. Put simply, the patent applications provided a ‘general blueprint’ for *manifesting* the technology. But they also provided a ‘checklist’ through which the orders of functions *defining the* technology could be *measured* theoretically (through simulations) and practically (through prototypes, and laboratory and test-track tests) and were ultimately optimized according to *evaluations* that made the theoretical and practical measurements of these different work arrangements relevant for each other. The development group was simultaneously designing a technology *towards* and *with* the patent applications’ finite and specific orders of functions, in a coordinated process that de- and re-stabilized the product-variant-cum-proof-of-concept until it could perform as a *boundary object* - maintaining relevance across different work arrangements without further adjustment.

This case fosters insights into how technical competencies to position and manipulate objects enable design and innovation in processes of technology development in ways that process models and figures of merit do not. While decision-making tools take for granted that such technical competencies and insights are readily available for selection, promotion and control (Clausen and Yoshinaka 2009), this case demonstrates how other objects – as embodiments of technical acuity – can enable design and innovation through mediation and coordination. Superficially, this idea of *positioning objects to perform coordinative action* can appear more arduous or chaotic than other mechanistic approaches to development, which often focus on *ready-made process models* in complex interactions with *off-the-shelf figures of merit* (see Browning et al. 2002; Cho and Eppinger 2005). But this assumes some type of 'general relevancy' across diverse spaces of technology development and neglects any necessary adjustments to ready-made models for specific, unforeseen or novel contexts. This industrial case demonstrates that even when development projects are officially paced or defined by decision-making tools, like NPD process models or TRL, other objects must still be positioned and manipulated in order to circumscribe agencies, organize encounters and establish the conventions upon which future decisions will rest. By placing the supposed essentiality of the process-models and figures of merit permeating industry in a more realistic context, the article sensitizes attention toward *how* industrial practitioners solve 'problems at hand' with 'objects on hand'. But it also provides theoretical reflection upon how practitioners place the principle intentions of their own work arrangements into larger perspectives than simply completing or achieving a generic *gate*, *level* or *phase*.

In conclusion, I suggest that the concepts of objects used to analyze coordinative action in this industrial case can assist technology managers and engineers in understanding and improving the nature of this work in their own practice. *Boundary objects* are a useful perspective by which practitioners can consider how diverse parties *adapt shared intentions* to their own local contexts, constraints and exigencies *without* destabilizing the common identity of these intentions across the concerned parties. The notion of *intermediary objects* provides a means for practitioners to consider and recognize the reciprocating roles of the objects they place into circulation, that they might better respond to, and ideally shape, *commissioning* and *mediating* roles of these objects. Finally, *equipping* can serve as a theoretical lens through which practitioners can focus on the *features* that their intermediary objects must obtain if they are to be effectively enrolled in the collective activities and exchanges of different parties. This type of reflection is particularly important for industrial practice, as engineers are often working intuitively – "produc[ing] knowledge that they themselves have difficulty explaining" (Vinck 2014: b).

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BIBLIOGRAPHY

Arbjerg, N., Ennemark, P., Frederiksen, M., Olesen, C.M., and Bates, C.A. (2018). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109794B4.

Bates, C.A. (2020, forthcoming). Staging with objects: Translation from technology to product development. In C. Clausen, D. Vinck, J. Dorland, and S. Pedersen (eds.). *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach*. Cheltenham: Edward Elgar Publishing.

Bates, C.A., Arbjerg, N., Ennemark, P., Frederiksen, M., and Olesen, C.M. (2018). *Hydraulische Lenkeinheit*. DE Patent No. DE102017109796B4.

Bates, C. A., and Clausen, C. (2020). Engineering Readiness: How the TRL Figure of Merit Coordinates Technology Development. *Engineering Studies*, 12(1), 9-38.

Bates, C. A., and Juhl, J. (2020, forthcoming). Staging referential alignment in industrial-academic collaboration. In C. Clausen, D. Vinck, J. Dorland, and S. Pedersen (eds.). *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach*. Cheltenham: Edward Elgar Publishing.

Borg, M., Badr, I., and Royle, G. J. (2012). The Use of a Figure-Of-Merit (FOM) for Optimisation in Digital Mammography: A Literature Review. *Radiation protection dosimetry*, 151(1), 81-88.

Bowker, G.C., and Star, S L. (1996). How Things (Actor-Net) Work: Classification, Magic And The Ubiquity of Standards. *Philosophia*, 25(3-4), 195-220.

Bowker, G.C., and Star, S.L. (1998). Building Information Infrastructures For Social Worlds—The Role of Classifications and Standards. In T. Ishida (ed.).*Community computing and support systems*. Berlin: Springer, 231-248.

Browning, T.R., Deyst, J.J., Eppinger, S.D., and Whitney, D.E. (2002). Adding Value in Product Development by Creating Information and Reducing Risk. IEEE Transactions on engineering management, 49(4), 443-458.

Callon, M. (1984). Some Elements of A Sociology Of Translation: Domestication Of The Scallops and the Fishermen of St Brieuc Bay. *The sociological review*, *32*(1_suppl), 196-233.

Callon, M. (2002). Writing and (Re)writing Devices as Tools for Managing Complexity. In J. Law, and A. Mol (eds.) Complexities: Social Studies of Knowledge Practices. Durham: Duke University Press, 191-217.

Callon, M., and Muniesa, F. (2005). Peripheral vision: Economic markets as calculative collective devices. *Organization studies*, 26(8), 1229-1250.

Cho, S.H., and Eppinger, S. D. (2005). A simulation-based process model for managing complex design projects. *IEEE Transactions on engineering management*, *52*(3), 316-328.

Christiansen, J. K., and Varnes, C. J. (2007). Making decisions on innovation: meetings or networks?. *Creativity and Innovation Management*, 16(3), 282-298.

Clausen, C., and Yoshinaka, Y. (2009). The Role of Devices in Staging Front End Innovation. In *Proceedings of the First International Conference on Integration of Design, Engineering and Management for*

Innovation IDEMI09. Porto: FEUP Faculty of Engineering and Management of the University of Porto, 1-8.

Cooper, R.G. (2014). What's Next?: After Stage-Gate. *Research Technology Management*, 57:1, 20-31

Danfoss A/S (2019). Orbital principle. *Danfoss Power Solutions steering solutions*. Nordborg: BU Steering. (Propriety training presentation).

Danfoss A/S. (2017). *Steering General, Steering Components*. Nordborg; Danfoss A/S.

De Laet, M., and Mol, A. (2000). The Zimbabwe bush pump: Mechanics of a fluid technology. *Social studies of science*, 30(2), 225-263.

Ennemark, P., Liljenberg, S., Rudolph, T., Tychsen, T., Vester, J. (2016a). *Hydraulic Steering System*. US Patent No. US9950737B2.

Ennemark, P., Liljenberg, S., Rudolph, T., Tychsen, T., Vester, J. (2016b). *Hydraulic Steering System*. US Patent No. US10161425B2.

Frederiksen, M., Ennemark, P., Olesen, C.M., Arbjerg, N., and Bates, C.A. (2018). *Hydraulische Lenkeinheit*. DE Patent No. DE102018112044B3.

ISO. (2012). *1219-1:2012(en) Fluid power systems and components — Graphical symbols and circuit diagrams — Part 1: Graphical symbols for conventional use and data-processing applications*. Geneva: International Organization for Standardization

Jernewicz, J. (2005). Humormennesket Storm P. In *Jernesalt*. Retrieved April 29, 2020, from http://www.jernesalt.dk/stormp-essay.asp.

Law, J. (2009). Actor network theory and material semiotics. *The new Blackwell companion to social theory*. Hoboken: Blackwell Publishing Ltd, 141-158.

Law, J. (2011 [1986]). On power and its tactics: a view from the sociology of science. In *Heterogeneities DOT net*. Retrieved July 26, 2020, from http://www.heterogeneities.net/publications/Law1986OnPowerAndItsTactics.pdf.

Mankins, J.C. (2009). Technology readiness and risk assessments: A new approach. Acta Astronautica, 65(9-10), 1208-1215.

Olechowski, A., Eppinger, S. D., and Joglekar, N. (2015). Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities. In *2015 Portland international conference on management of engineering and technology (PICMET)*, 2084-2094.

Narayanamurti, V., and Odumosu, T. (2016) *Cycles of Invention and Discovery*. Cambridge: Harvard University Press.

Star, S.L. (2010). This is Not a Boundary Object: Reflections on the Origin of a Concept. Science, *Technology, and Human Values*, 35(5), 601–617.

Star, S.L., and Griesemer, J.R. (1989). Institutional ecology, translations and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social studies of science*, 19(3), 387-420.

Szajnfarber, Z., and Weigel, A.L. (2013). A Process Model of Technology Innovation in Governmental Agencies: Insights From NASA's Science Directorate. *Acta Astronautica*, 84, 56-68.

Verworn, B. and Herstatt, C. (2002). The innovation process: an introduction to process models. *Working Papers / Technologie- und Innovationsmanagement, Technische Universität Hamburg-Harburg*, No. 12.

Vinck, D. (2009). *Everyday Engineering: An Ethnography of Design and Innovation*. Cambridge: MIT Press.

Vinck, D. (2011) Taking Intermediary Objects and Equipping Work Into Account in the Study of Engineering Practices. *Engineering Studies*, 3:1, 25-44.

Vinck, D. (2012). Accessing material culture by following intermediary objects. In L. Naidoo (ed.), *An Ethnography Of Global Landscapes And Corridors*. Chicago: InTech Publishing, 89-108.

Vinck, D. (2014). Engineering practices: The Knowledge of Action. *Revue d'anthropologie des connaissances,* vol. 8, 2(2), a-s.

Vinck, D., Jeantet, A., and Laureillard, P. (1996). Objects and Other Intermediaries in the Sociotechnical Process of Product Design: An Exploratory Approach. *The role of design in the shaping of technology*, 5, 297-320.

Williams, R., and Edge, D. (1996). The Social Shaping of Technology. *Research policy*, 25(6), 865-899.

Appendix E. Referential Alignment: Situating Knowable Materialities in Innovation Science

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Abstract

Despite institutionalized relations between research and innovation in terms of funding structures, spin-off offices and science parks, there is relatively little qualitative insight of how knowledge is produced and used for commercial ends within industrial-academic collaboration and only limited understanding of how to recognize and guide the content and direction of research within such contexts. Drawing on recent ethnographic studies of the collaboration between a large Danish hydraulic manufacturer and a leading Swedish tribology research group, as it was led by the second author, this paper presents how these partners attempted to bring a new environmentally friendly lubricant technology to market. In contrast to more traditional interpretations of scientific knowledge practices that build on claims of (relative) universality and objectivity, the analyses presented here examines how collaborating partners worked towards establishing conditions for transferability between their situated knowledge practices. By drawing on the notion of 'Innovation Science' (Juhl 2016), and concepts from feminist epistemologies (Barad 2003; Cartwright 1999); Haraway 1991) that are attentive to the situated and contestable nature of knowledge production, this paper develops a situated interpretation of knowledge that enable us to analyze the contingencies of both scientific and industrial epistemologies. Finally, the paper theoretically conceptualizes the term 'referential alignment' (Bates and Juhl 2020) to account for the mechanism through which knowledge and technology are made transferable in collaborative innovation.

Keywords: Industrial-academic Collaboration; Innovation Science; Referential Alignment; STS; Technology Development

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INTRODUCTION

In contemporary science and innovation politics, academic knowledge production and economic growth is almost seen as synonymous. As a consequence, one of OECD's benchmark indicators is the gross national investment in research and development. The percentage of a country's gross domestic product (GDP) that goes into research is used as an indicator of the country's innovation capacity and thus it's economic competitiveness. Such assessment practices have produced not only standards and targets for national investments in research, but also intensified a 'catching up' agenda where countries implement economic policies to increase their total investment of GDP in research (Pfotenhauer et. al 2019). The European Union has through two decades maintained a strong emphasis on increasing its investments in research in its efforts to match the 3 % of GDP observed in Japan and the US (Rodriguez et al. 2010). However, while the relation between research and innovation has been institutionalized through funding structures, spin-off offices and science parks, there is little qualitative insight into how knowledge is produced and used for commercial ends within industrial-academic collaborations. As a result, there is limited understanding of how to manage the content and direction of research in the context of commercial innovation. Where Science and Technology Studies historically has done much to open up scientific knowledge productions through empirical studies of academic scientists' and engineers' micro-processes in scientific laboratories (Latour and Woolgar 1986, Knorr-Cetina 1999) and academic institutions' governance processes (Strathern 2000, Carney 2006), comparatively much less attention has been directed towards industrial knowledge-making and its connection to commercialization of science.

Despite that the political focus on national investment in scientific research has been continually practiced since the end of World War 2, the underlying political and economic thinking has changed drastically. The American post WW2 vision of science was about securing basic research. Scientific results were envisaged as an apolitical intellectual resource that private industry would turn into technological innovation and economic growth (Pfotenhauer and Juhl 2017; Bush 1945). Whereas initial ideas were built on separate responsibilities between publicly funded research and private commercialization, later positions on public funding of research saw academia and industry as closely entangled systems of production. Gibbons et. al (1994) coined the term 'Mode 2' knowledge production to distinguish what they saw as a new form of collaborative research practice that was organized around problem contexts within society. In opposition, they called the old paradigm 'Mode 1' which they characterized as disciplinary and university centered. The shift from Mode 1 to Mode 2 represented a change in the moral criterion that underwrote scientific work. From securing scientific institutions' political insulation in Mode 1, Mode 2 was about ensuring science's practical utility and perceived value to society through direct interaction with non-scientific collaborators. Later, with the introduction of the Triple Helix model for national innovation systems, Etzkowitz and Leydesdorff (2000) further modified the moral imperative for scientific research by situating universities as centers within what they perceived as a hybrid space for university-industry-government interactions. According to the Triple Helix idea, governments and policymakers should work to erode institutional boundaries between what the authors saw as the formerly distinct spheres of academic research, private industry and government.

Under the banner ‘From research to invoice’ the Danish Government implemented several new university laws and reforms in the early 2000s. The result was that the public Danish universities effectively were turned into autonomous institutions that were responsible for their own economy. First with the DTU law in 2000, then the researcher’s patent law in 2001, which in 2003 was followed by the reform: ‘Time for transformation of Denmark’s universities’. Together they underwrote a new sensibility and rationality behind publicly funded scientific research that was modelled on private corporate structure. The old system’s democratic principles, where researchers, teachers, students and non-academic staff all had a say in university-matters, was removed. The new system built on a professionalized top-down administration with an executive board consisting mostly of external members from industry. In the following years, Denmark’s public funding intensively turned towards competition distributed grants. By 2006 more than 50% of Denmark’s total public spending on science was to be competition based (Caney 2006, Pfotenhauer et. al 2019). This enabled the Danish Government to more directly govern the direction of publicly funded research by channeling more economic resources and decision-authority through politically controlled funding agencies. When public funding agencies including, but not limited to ‘the innovation fund’ and ‘the industry fund’ required substantial industrial involvement and elaborate business plans based on commodification schemes, academic researchers were left with little other choice than to collaborate with industry as a service to solving industrial problems for commercial ends. As captured by the term *Innovation Sci*ence (Juhl 2016), this particular service relationship between academic science and commercial problems, has consequences the for kinds of problems and results that academic scientists are justified to work with.

Despite the long-standing political and academic interest in the interaction between academic research and industry, existing studies predominantly treat the structural conditions that surround scientific and industrial partners. Comparatively, much less attention has been given to the qualitative characteristics of such collaborations’ inner operations and what public-private partnerships mean for the content and the quality of the work being conducted. In answer, ethnographic studies of collaborative practices between industrial and academic partners (Juhl 2013) culminated in the notion of *Innovation Science* that denotes a “domain of knowledge production… [where] academic scientists produce knowledge for commercial ends” (Juhl 2016: 29). By analyzing the translation of exchanges between the collaborating academic and industrial partners, including how these exchanges produced new translations within each environment, innovation science presents a practice-near and micro-process-based account of how the dynamics of values, interests, epistemologies and challenges can be interpreted within science-industry collaborations. On the recognition that scientists and industrialists work under different performance criteria, innovation science points out the importance of abilities, to develop shared success parameters with regards to the coordination of exchanges of intermediate results across different institutional and professional settings. This is seen as central for the abilities of collaborating partners to define their respective means and ends towards achieving overarching objectives. On the recognition of this importance of shared success criteria for coordinating heterogeneous collaboration's intermediary objectives and exchanges, the next line of inquiry concerns the means through which shared criteria are met.

A NEW HYDRAULIC LUBRICANT FOR THE OFF-HIGHWAY MOBILE INDUSTRY?

The empirical case that we will use to examine the features and mechanisms of science-industry knowledge-making concerns a collaboration between tribological scientists and engineers from Luleå University of Technology (LTU) in Sweden, the mobile hydraulic segment of the Danish manufacturer Danfoss Power Solutions (DPS), and Sustainalube AB, an LTU spin-off company. The collaboration was initiated by LTU under the understanding that replacing standard hydraulic fluids with a new environmentally friendly non-petroleum lubricant developed by Sustainalube would require cooperation with the mobile hydraulic industry. As a technology leader and venerated brand within this industry, tests performed at DPS were important for demonstrating the functionality and reliability of the new environmentally friendly lubricant. Initially, the collaboration between DPS, LTU and Sustainalube was intended to validate the functionality and reliability of the new lubricant by documenting its (assumedly positive) effects on the magnitudes and types of wear on hydraulic components. When early, unexpected wear-results undermined this intention, the scope of the collaboration transitioned into efforts to re-develop the non-petroleum lubricant towards performance criteria which *de facto* supported the dominant petroleum based hydraulic fluid that permeates the mobile hydraulic industry see – Bates and Juhl (2020 forthcoming) for the details of this transition.

The scope of this paper is to examine and conceptualize collaborative knowledge production in technology development between academic researchers and industrialists. Characteristic for collaboration between scientific and industrial partners is that partners operate within different organizational and institutional settings and adhere to different performance criteria (Juhl 2016). The collaborative outset of the presented case was a series of technology tests. The tests were initially performed to demonstrate functional reliability of a new lubricant but were later extended towards deeper theoretical understandings of lubrication standards and attritional effects. The point at which the present analysis enters the case, is where the technology tests surprised by producing results that required theoretical remodeling of the non-petroleum-based lubricant. The implication of this unexpected turn was that that the theoretical understanding and practical knowhow about how to tune lubricants proved insufficient for non-petroleum-based lubricants. In effect, much of the knowledge base upon which the collaboration's tribology and mobile hydraulic expertise was built had to be reassessed in order to scrutinize the conditions under which the behavior of the new environmentally friendly lubricant could be known and understood in relation to industrial implementation. Initially, the LTU-DPS collaboration centered on transferring the novel scientific lubricant technology into the industrial setting where its interaction with industrial components was meant to generate experiences applicable to its industrial implementation. However, with the unexpected test fallout, the collaboration turned towards a deeper re-working of the conditions underwriting the partners' respective knowledge-making.

By analyzing the planning and execution of the consolidation of the academic and industrial knowledge practices, we seek to understand the mechanisms that can be understood to connect situated knowledges (Haraway 1991) across different collaborative environments. The relationship between the test objects and the requirements of the collaborating environments was thereby central in order to understand the collaborative multi-sited knowledge production.

TECHNOLOGICAL, EXPERIMENTAL AND SITUATED KNOWLEDGES

Through the analytic scope of *innovation science,* we scrutinize the performative nature of knowledge production. "In contrast to pure academic science that produces universal knowledge, innovation science produces knowledge that is particular to its intended application environment" (ibid: 137). Innovation science touches upon an inherent tension within science-industry collaboration's epistemic setup. Because science and industry are institutionally set up to have different uses for knowledge and different settings for its applicability, the epistemic requirements that they each apply to knowledge are different. In short, for science to produce knowledge, which validity is considered to apply as broadly and (universally) as possible, scientific practice tends to work towards eradicating the variations that are attributed to the results by the local and situated circumstances of its production. However, within industry, it is typically these local and situated circumstances that form the premise under which knowledge is required to apply. The analytic approach in the paper is to trace the work that connects the production and exchange of knowledges between different situated conditions with each their own local, material, cultural and epistemic specificity. By observing both scientific and industrial knowledge productions as situated practices, the analytic objective is to better understand how the same results are made to apply as relevant and robust knowledge under both industrial and scientific conditions and requirements.

The theoretical question that underwrites the empirical analysis is: How did a distributed knowledge production establish a referential infrastructure that enabled its participants to produce coherent results that applied across their different situated practices? On a practical level, how did this infrastructure provide the necessary connectivity and transferability that could satisfy the diverse organizational, institutional and epistemic requirements between the off-highway mobile industry and the scientific field of tribology?

The present paper examines how the collaboration produced what we term ‘referential alignment’ (Bates and Juhl 2020 forthcoming) between the involved participants and their situated knowledge practices. Referential alignment is a concept for the operational principle that we develop to explain how knowledge infrastructures enable standards and objects to move and refer and forth between diverse situated knowledge practices. ‘Referential alignment’ refers to the quality of referential relationships that enable knowledge artefacts and processes to inter-act (Barad 2003) within different situated, material, organizational, local and temporal settings. We see referential alignment as critical to enable knowledge exchanges between distinct epistemic cultures and situated practices - e.g. between industry and academia. By studying how off-highway mobile industry and the scientific field of tribology worked to become referentially aligned and thus synchronized at an ontological and epistemological level, we seek a better understanding of how knowledge practices are conditioned to co-operate across different disciplinary and professional boundaries.

Bruno Latour introduced the concept ‘Circulating Reference’ as an explanation for what he saw as the modus operandi behind scientific practice. According to Latour, science’s epistemic principles work by scientists’ construction of references. By bringing matter and language together in hybrid networks, scientists produce relations between local materially complex conditions in one direction and standards, texts, calculations of relative universality in the other direction (Latour 1999). The common operator throughout each step in the construction process is the ‘message’ that is amplified by the network of things and signs. According to Latour, this message manifests itself throughout the cascades of translations of matter-sign vehicles that make up the scientific practice. Latour’s empirical demonstration of Circulating Reference however stays within the consolation of established field science practices. While the empirical site and the research question presented novelty, the methods underwriting the scientists’ translation of the forest into a field laboratory fits with Latour’s own characterization of ‘readymade science’ (Latour 1987). Readymade science means that the scientific field has settled its controversies surrounding its methods and standards so that these can be applied to give answers. Latour’s metaphor for readymade science is that of railroads, upon which science can move fast and effectively – but only where tracks have already been laid. A similar idea was proposed by Rheinberger (1997) who termed such established scientific approaches as ‘technical objects’, or ‘answering machines’. These were instrumental in order to condition and bring into being novel ‘epistemic things’ -the subjects of investigation and scientific scrutiny. Readymade science means that norms for interpretation and evidential requirements are established prior to the experiment and are considered stable enough for other 'matter into form translations' to be built upon them. In contrast, when we examine how referential alignment is established in technology tests conducted by both scientists and industrialists, the activity better resembles 'science in the making' (ibid). Science in the making means that facts and machines are still 'under-determined' and shared norms for interpretation and evidence have yet to be established. No railroad tracks have yet been laid – so to speak.

Despite the dissimilarities between Latour's Boa Vista case and innovation science, the problem of establishing references between material manifestations and their conceptual representations, is still productive. By studying how material environments are conditioned to behave so that properties of objects and processes become observable, we extend the analytic idea of hybrid matter into form - translations, to work in multiple directions and between different distinctly different material, epistemic and normative situated conditions. In other words, we aim to extend Latour's hybrid conception of knowledge processes to encompass the hybridity and multiplicity of heterogeneous science-industry knowledge productions.

As earlier indicated, one of the characteristic differences between traditional scientific knowledge production and industrial knowledge practices, is the status of the local, particular and material conditions that relate to knowledge practices' situated nature. In traditional science, the epistemic hierarchy dictates the local conditions to mainly function as a site of extraction, where material specimens are collected, measurements are performed and inscribed in order transport them to sites where they can be stored, preserved, processed, compared and analyzed (Latour 1999). The local thus acts as a material anchor point for the network of references, which ensures that the abstractions refer to 'real' data points. In comparison, industrial knowledge practices have a distinctly different position on the status of the local. For industrial productions, their potential as sites of data extraction is secondary to their main function, which is to produce commercial value through commodities. For the data to be relevant to the industrial production sites, it needs not only to refer to the site's local conditions, but also to make knowledge that applies to the site by resulting in tangible production improvements. To industry, the local, contextual and situated conditions function as a catalyst for practical validation through tangible production impacts.

Through her work on situated knowledge, Donna Haraway echoes the importance of the locally and temporally situated position from which knowledge is produced and qualified. According to Haraway, it is by acknowledging the contingency of the subjects' own position in the world that at one and the same time grants the possibility for greater objectivity than claiming to be a neutral observer and possessing a perspective from 'nowhere'. In return, Haraway's situated position also makes for the contestable nature of the subject's claims.

Haraway (1991) calls it reductionism when one language must be enforced as the standard for all the translations and conversations. Reductionism has led to 'powerful mental orders of global sciences', which serves as a 'service to hierarchal and positivist orderings of what can count as knowledge' (ibid: 188). Though her insistence on the *embodied nature of all vision*, Haraway argues 'for a doctrine and practice of objectivity that privileges contestation, deconstruction, passionate construction, webbed connections, and hope for transformation of systems of knowledge and ways of seeing.' (ibid: 191). Put simply, Haraway is 'arguing for politics and epistemologies of location, positioning, and situating, where partiality and not universality is the condition of being heard to make rational knowledge claims.' (ibid: 195). While Donna Haraway argue for the subject's situated nature and positioned partiality as an ontological premise for knowledge, Nancy Cartwright (1999) echoes the idea of 'partial realism' in her critique of positivist knowledge systems with her infamous notion: 'why physics lie'.

According to Cartwright 'the laws of physics' fall short of describing reality because they fail to inform us what the objects within this domain *do*. Instead of the reality that we can observe outside highly specialized laboratory settings, scientific laws describe highly idealized objects in theoretical models. According to Cartwright, the world needs to be manipulated to produce the order that we know as physical laws. An arrangement that produces this sort of manipulation is what Cartwright (1999: 50) terms a *nomological machine*: 'a fixed (enough) arrangement of components, or factors, with stable (enough) capacities that in the right sort of stable (enough) environment will, with repeated operation, give rise to the kind of regular behavior that we represent in our scientific laws'. Thus, it is the function of the laboratory arrangement that reproduces the regularities we know as physical law. In Cartwright's metaphysics, the notion of partial realism or 'entity realism' is based on the understanding that theoretical entities can be founded in well-tested localized causal claims about concrete physical processes. Whereas Haraway's ontology of observation stresses the local, partial and positioned view in situated knowledge, Cartwright contributes with a localized epistemology that recognizes how particular delimitations and constraints of specialized conditions make it possible for physical laws to be observable as the regular – one could even say *regulated* – behavior of idealized objects in theoretical models.

The take home from Cartwright's epistemology is the 'local' and 'partial' nature of the conditions under which scientific laws hold. Cartwright's philosophy thereby underwrites Haraway's position on the unrealistic idea of universal claims that can travel unhindered and unbiased to everywhere by claiming to hold a 'god like' perspective from 'nowhere'. Cartwright ties 'physical laws' to the local conditions of their manifestation and thereby underlines the importance of those exact conditions for knowledge claims to hold. This brings attention to the necessity of having exact (enough) conditions elsewhere in order for knowledge claims that are produced in one local setting to be able to hold other settings with unique local particularities.

In Karen Barad's (2003) performative philosophy, apparatuses are 'material discursive' – they produce determinate meanings and material beings that exclude the production of others. Positing the idea of 'agential realism', Barad sees the universe as comprised of phenomena, which are defined through the 'ontological inseparability of intra-acting agencies'. To Barad, objects and phenomena emerge through particular intra-actions. Similarly, to Cartwright, Barad argues that phenomena are produced by apparatuses – for example laboratory installations.

> For Bohr, apparatuses are particular physical arrangements that give meaning to certain concepts to the exclusion of others; they are the local physical conditions that enable and constrain knowledge practices such as conceptualizing and measuring; they are productive of (and part of) the phenomena produced; they enact a local cut that produces "objects" of particular knowledge practices within the particular phenomena produced (ibid: 819).

Moving beyond simple accounts of phenomena as being compromised of humans and non-humans, Barad's analytic interest is rooted in the conditions of possibility that arise for humans and non-humans within their materiality and not merely as ideational concepts in the discursive realm:

> The move toward performative alternatives to representationalism shifts the focus from questions of correspondence between descriptions and reality (e.g., do they mirror nature or culture?) to matters of practices/doings/actions. I would argue that these approaches also bring to the forefront important questions of ontology, materiality, and agency, while social constructivist approaches get caught up in the geometrical optics of reflection where, much like the infinite play of images between two facing mirrors, the epistemological gets bounced back and forth, but nothing more is seen. Moving away from the representationalist trap of geometrical optics, I shift the focus to physical optics, to questions of diffraction rather than reflection. […] I offer an elaboration of performativity […] that allows matter its due as an active participant in the world's becoming, in its ongoing "intra-activity"' (Barad 2003: 802-803).

In Barad's philosophy, distinctions are produced through what she calls 'agential cuts' that are performed by the specific material configuration of the 'apparatus of observation'. Whereas Barad sees 'Cartesian cuts' as implying an inherent distinction between object and subject, she presents *agential cuts* as enacting a local resolution within the phenomenon of the inherent ontological indeterminacy. Intra-actions enact 'agential separability', which is a local condition of *exteriority-within-phenomena* that is fundamental for providing objectivity in the absence of the classical ontological condition of object and observer. According to Barad (2003: 815), 'the agential cut enacts a local causal structure among "components" of a phenomenon in the marking of the "measuring agencies" ("effect") by the "measured object" ("cause")'.

Barad's philosophy places the gravitas of explanation within the local intra-action of the situated material conditions. Rather than philosophical constructs that are inherently based on language and human discourse, Barad moves the locus of the referential problem to its material properties and dynamics. Observation become a consequence of material behavior and is not in itself a condition. Another important insight from Barad (2003) is that conditions of possibility connect with intra-activity as a form of *indeterminist* condition where outcomes of arrangements may fall within a complex range of possibilities – rather than just one definite discrete result. This perspective attends to how entities hold, what in philosophy of science, is also called 'capacities' and presents an alternative to the idea of determinate physical properties. It is thus the combined effect of an entity's capacities and the conditions of the apparatus within which the entity resides that accounts for the entity's observable behavior. This is also evident in Cartwright's thinking (1999: 65):

> I say that Newton's and Coulomb's principles describe the capacities to be moved and to produce a motion that a charged particle has, in the first case the capacity it has on account of its gravitational mass and in the second, on account of its charge.

Cartwright's conception of a material entity possessing certain *capacities* has in common with Barad's notion of intra-activity that the material arrangements wherein entities intra-act form certain conditions for the involved entities' respective capacities to behave in particular ways. Even a minor alteration in such an arrangement can thereby result in radically different systemic behavior – as a consequence of shifting balances between the intra-acting capacities. It is attention to this kind of complexity that necessitates a situated perspective on knowledge that is not only sensitive to, but conditioned by, local and particular of practices and arrangements. The situated perspective on knowledge that we contemplate sees the material arrangements and practices as constitutive for any meaningful conception of what it means to know. Consequently, we see knowledge as integral to the practices wherein it is developed and put to use. Knowledge is neither cause nor effect of human practices but rather an abstracted layer of practices that we, especially in the western world, have a cultural bias for trying to analyze through language. However, abstraction into words is not to be confused with the underlying, and far more complex phenomena, that it is trying to 'capture'. This resonates with Rouse (2002), who proposes an understanding of scientific practice as ongoing patterns of situated activity:

> The presumption that we can know what we mean, or what our verbal performance say, more readily than we can know the objects those sayings are about is a Cartesian legacy, a linguistic variation on Descartes's insistence that we have a direct and privileged access to the contents of our thoughts that we lack towards the "external" world (ibid: 209).

In the following empirical analysis, we direct attention to the specifics of local material configurations. By focusing on industrial test rigs and scientific laboratories, we explore how these come to work as *apparatuses of observation* and examine how they perform *agential cuts* that enact local resolutions within the phenomena of *intra-acting* material entities. Intra-actions are seen to enact *agential separability*, which produce the local condition of exteriority-within-phenomena that make distinctions observable to the scientists and industrialists. 'Observation' is viewed as an inherent feature of agential separability. This notion is fundamental for a situated understanding of objectivity that moves beyond the classical ontological condition of object and observer. By seeing agential cuts as enacting local causal structure among *components* of a phenomenon and marking the *measuring agency* by the *measured object*, we interpret the material configuration and intra-agency of tests and experiments as responsible for the *possibility* of observations. This calls for an alignment at the materially discursive level so that the relevant intra-actions within one site might produce the same agential cut as the relevant intra-actions in the other site. In the following analysis we will show how this has been obtained through what we call 'referential alignment', which we seek to establish within a situated knowledge perspective, in order to account for the inherent difficulty in making knowledge and technology that can be produced and applied across different situated practices.

MULTI-SITUATED KNOWLEDGE PRODUCTION: MAKING RELIABLE SCIENCE AND KNOWABLE TECHNOLOGY

In the case considered here, pursuing referential alignment required that relations between key technological and knowledge artifacts could be circumscribed and made relevant for both the specific and common needs of academic scientists and industrial engineers. The plan of action formulated by the industrial-academic collaborators was deceptively simple. The industrial partner (DPS) would combine their component and process expertise with 3D surface roughness measurements made by the academic partner (LTU) to manufacture discs that could be correlated with DPS gear-sets according to the specifications of the LTU ball-on-disc device. The idea was to connect the DSP manufacturing process as a condition for the scientific instrument's measurements of the new lubricant. This meant that friction coefficients and other central parameters would be produced under material conditions similar to those present within the hydraulic motors produced by DPS. Sustainalube would then utilize this new *ball-on-disc* data to molecularly tune their new lubricant in order to validate the lubricant as a possible substitute for the standard ISO 32 oil that dominates the mobile hydraulic industry.

Brief introductions to the key technological and knowledge artefacts follow here.

ORBITAL GEAR-SETS – THE TECHNOLOGY IN THE MIDDLE OF MARKET AND SCIENCE

According to Barad (2003: 815), 'It is through intra-actions that the boundaries and properties of the "components" of phenomena become determinate and that particular embodied concepts become meaningful'. In this industrial-academic collaboration, re-developing the Sustainalube lubricant for utilization in the off-highway mobile industry would entail validating the novel lubricant's functionality and reliability in a hydraulic 'orbital motor'. Hydraulic motors convert hydraulic energy, in the form of pressure and oil flow, into mechanical energy, in the form of torque and speed. An orbital motor is a type of hydraulic motor where energy conversion occurs through a mechanism consisting of a gearwheel and a gear-rim, where the gear-wheel rotates about its own center while simultaneously orbiting on a circle with the same center as the gear-rim (see figure 1). This orbital movement is achieved by switching between high and low pressure in the chambers of the gear-set which 'pushes' the gear-wheel around the inside of the gear-rim in clockwise or counter-clockwise directions of rotation. Contact between the gear-wheel and gear-rim is a combination of sliding and rolling, where an oil-film of varying thickness occurs between the components, or doesn't – this is known as *mixed lubrication*. These effects cause wear, which can reduce efficiency of the motor and in the worst-case lead to seizure. DPS and LTU had previously collaborated to understand and simulate wear-mechanisms of this complex tribological system that is comprised of only three components: the gear-wheel, gear-rim and hydraulic lubricant (see Furustig et al. 2015a, 2015b). The immediate effects of changes to any one of these components made this type of hydraulic motor uniquely suited to developing and qualifying the lubricant. The orbital principle stems from a patent taken over 60 years ago (Charlson 1958), orbital gear-sets persist as a cornerstone of the off-highway mobile industry and remain the subject of extensive academic research (Gamez-Montero et al. 2019).

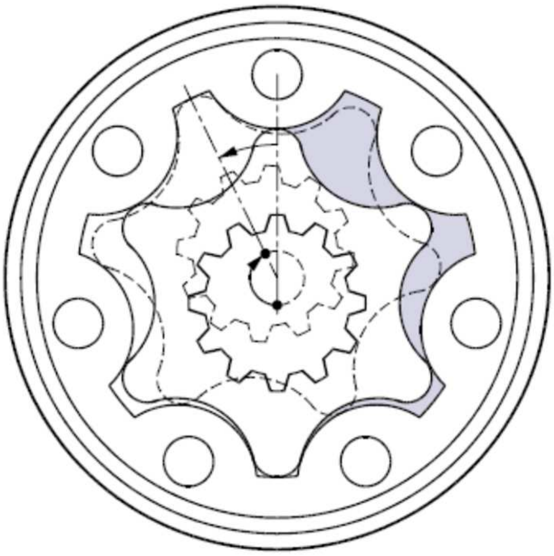

Figure 1: Illustration of an orbital gear-set from a technical brochure (Danfoss A/S 2015: 8). Excentricity between the gear-wheel and gear-rim enable the orbital movement for which the principle is named.

A defining feature of an orbital motor is its robust ability to effectively generate work over a large area of application. One way of visualizing and communicating this information is through an industry standard used by Danfoss since at least 1973 (Danfoss A/S 1973). 'Shell Diagrams' illustrate the entire area of application for an orbital motor (see figure 2 below). Relationships between flow and speed, and differential-pressure and torque are shown on the X-axis and Y-axis, respectively. Superimposed over this grid are the curves for constant power output, plotted as hyperbolas, and the constant total efficiency (η T), shown as ring forms resembling the mussel shells for which the diagram is named. The white-filled circle demarcates a transition from continuous to intermittent pressure and speed – an area of application that may not occur more than 10% of each minute. Although different areas of application will result in significantly different types and magnitudes of wear, industry expectations require that any changes to the design of a motor or the system into which it is integrated (including the lubricant and its viscosity) do not significantly reduce, and ideally improve, the motor's durability (i.e. performance over time) across its entire area of application. Accommodating this feature proved a significant hurtle for the collaboration, already from its earliest phases. Here, seemingly well-founded assumptions that the frictional benefits of the novel lubricant which had been established in scientific test-setups made at LTU could be replicated in industrial test-setups at DPS proved exceedingly difficult to achieve (see Bates and Juhl 2020).

For new technology to enter an established market, it will be measured up against established standards that been developed in conjunction with the existing technologies. Our inquiry into the experimental testing of a new non-petroleum based lubricant technology has shown us the importance of the practice's inherent material discursive intra-action. Firstly, by demonstrating unexpectedly high degrees of gear-set wear, the molecular tuning of the lubricant was called into question. It's intra-action with the orbital gear set did not cooperate the lubricant's otherwise promising friction characteristics. This realization caused the collaborating partners to relocate their attention away from the industrial application of the new scientific break-through technology to instead question the scientific practice and the theoretical work behind the new technology.

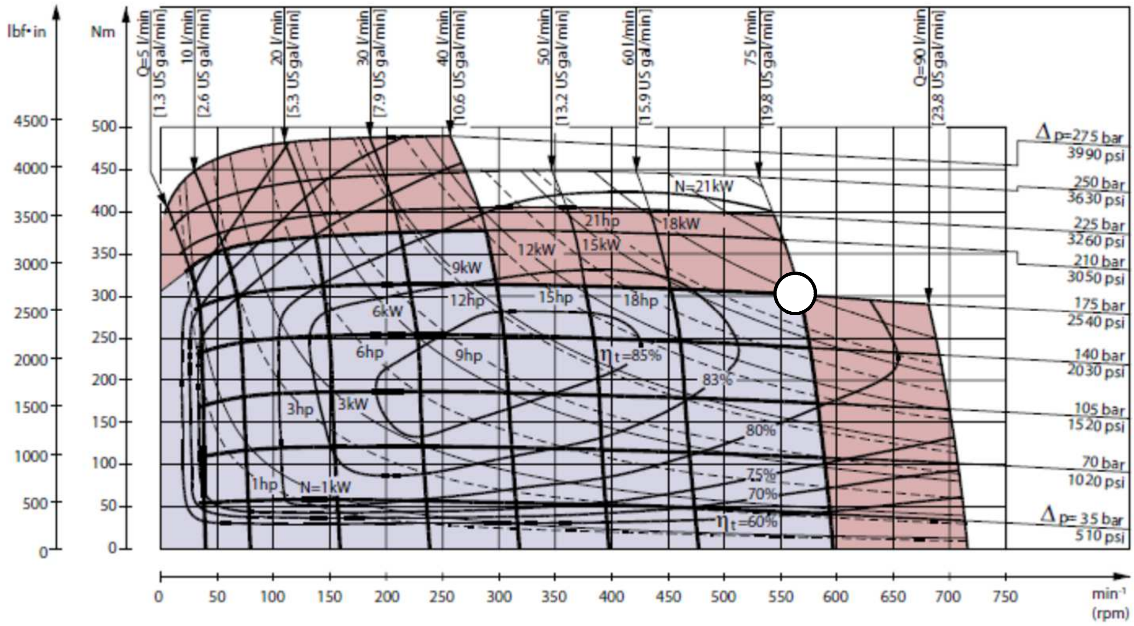

Figure 2: 'Shell diagram' illustrating an orbital motor's efficacy over its entire area of application (Danfoss A/S 2015: 17).

BALL-ON-DISC EXPERIEMENTS

In order to molecularly tune their lubricant, Sustainalube needed to ascertain numerous theoretical values related to performance characteristics under highly specific usage scenarios. Among these, the lubricant's pressure-viscosity coefficient (α) was of special importance. This is due to the high pressures under which an orbital gear-set operates and that high pressures have significant effects on both the viscosity of the lubricant and on abilities to model a lubricant's film thickness and friction characteristics (Lugt and Morales-Espejel 2011: 472). Unfortunately, simplified equations for this calculation lack accuracy and the more complex calculative alternatives require that multiple input parameters are measured in idealized contexts (ibid). While an accurate derivation of α was the initial raison d'être for instigating ball-on-disc experiments at LTU, the ball-on-disc experiments, once established as a means of action towards optimizing the new lubricant, opened for new and wholly different objectives for DPS. This is grounded in the specific usage scenarios from which necessary theoretical values must be ascertained. Because these scenarios could only be defined by DPS as realistic (albeit simplified) interactions between DPS components, the obtained theoretical values could feed directly into the company's practical simulation and modelling capabilities (Bates and Juhl 2020). The critical interaction between local Danfoss components meant that their recorded behavior gave way to theoretical values, which applicability was conditioned by the same situated application. However, due to unexpected gear wear, this seemingly simple plan of action (to fabricate test samples, extract theoretical values from ball-on-disc experiments, tune the lubricant, validate the lubricant on an industrially relevant test-setup and finally feed this data back into practical models) would ultimately challenge initial assumptions about the scope of the collaboration. Returning to Barad:

> Apparatuses are not inscription devices, scientific instruments set in plane before the action happens [...] Apparatuses are not static arrangements in the world, but rather apparatuses are dynamic (re)configurations of the world, specific agential practices/intra-actions/performances through which specific exclusionary boundaries are enacted (Barad 2003: 816, original italic and underscore).

MANUFACTURING ALIGNED SCIENTIFIC AND INDUSTRIAL KNOWLEDGE PRACTICES

Collaborating across scientific experiments and technology tests proved to be arduous. For ball-on-disc experiments, results are explicit to the samples upon which they are conducted. Consequently, the surface roughness characteristics and mechanical properties of either the ball or the disc (ideally both) need to be dimensioned according to the technology tests towards which they will be made relevant. In our case study, this was easier said than done. While LTU had conducted extensive ball-on-disc experiments to document the boundary and elastohydrodynamic lubricating behaviors for potential variants of the Sustainalube lubricant (Shi et al. 2014) using the test-setup illustrated in figure 3, these experiments were dimensioned according to the standardized ball and disc components commercially available to tribological laboratories. As such, the surface roughness characteristics and mechanical properties of these components were only *marginally representative* of the materials and manufacturing processes proliferating the hydraulic industry – as were the theoretical α-values they had generated. The fundamental challenge was that the university laboratory presented different material conditions than those present at DPS' test facility. When it came to friction parameters, the micro topology of interacting surfaces and materials were paramount for the specific situated intra-action. The specifics of the test gear-sets and the test rig was as much part of performing the agential cut against which wear became observable, as was the new lubricant that initially was to be tested. Similarly, the manufacturing of the metal items for the ball on disk test, was as much part of the friction properties that it made observable, as the lubricant was. For one site to become knowable in relation to the other, their specific situated conditions had to be aligned at a material level. To ensure this, the items used at each site and their specific topological traits, had to be products of the same situated manufacturing process. This was the operator behind making the industrial and university sites referentially align-able so that the theoretical friction properties would be applicable to the particular test rig at DPS.

Though the intricacies of fabricating industry relevant balls for experiments were

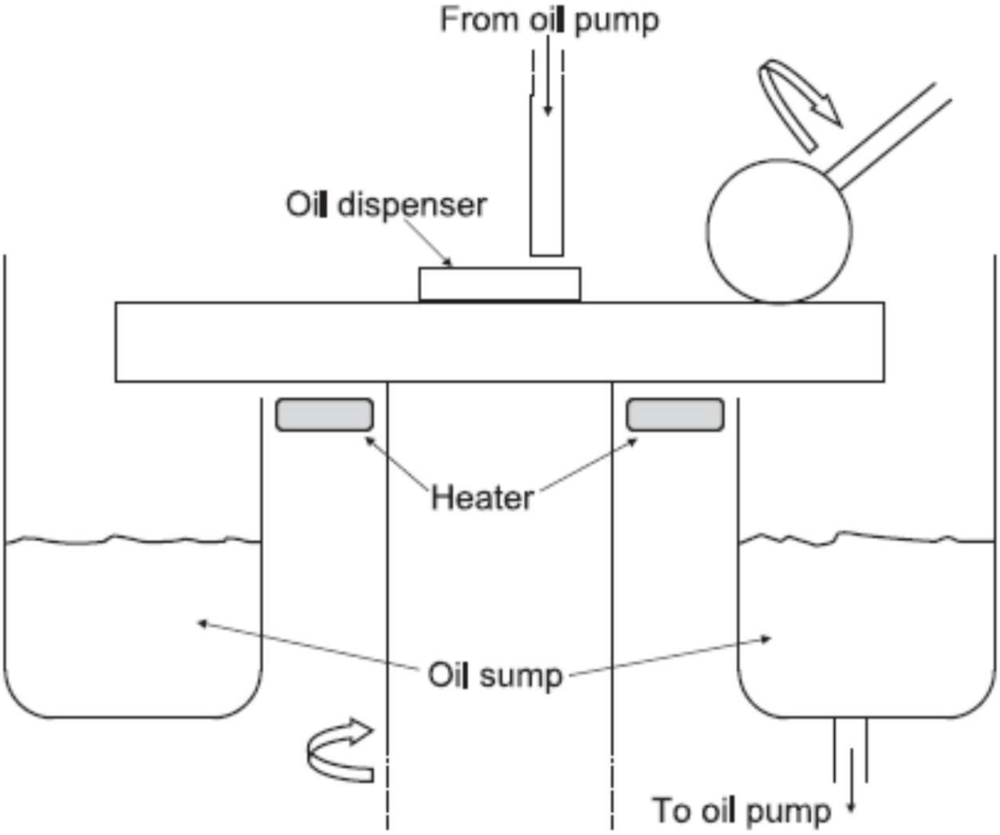

Figure 3: Schematic sketch of the LTU ball-on-disc device (Björling et al. 2011: 673), which allows for highly specific (albeit simplified) investigations of interactions between components with different surface finishes and mechanical properties across lubrication regimes.

wholly beyond the competencies of the collaborating parties, the fabrication of industry relevant discs by DPS was assumed feasible. Still, two unforeseen factors were particularly confounding for this assumption. Both were related to geometry. Experimental discs are defined as short cylinders with standardized parallelism, perpendicularity, diameter and height, and a concentric through-bore in the middle by which the disc can be fastened to a rotating shaft. For such discs, it is the flat planes at the *ends* of the cylinder which interface with the ball and discs. In contrast, hydraulic gear-wheels and gear-rims are typically fabricated from long cylinders (round-bar), were interactions between the two components occur on the machined *sides* of the cylinders (see figure 1). While LTU had already provided DPS with extremely accurate 3D surface roughness characteristics of their interfacing surfaces, the high-volume industrial processes used in gear-set fabrication are all developed towards manufacturing specific surface topographies on *profiles* (contra the required *planes*). DPS would thus need to develop temporary, one-piece production processes through which industrially relevant experimental discs could be fashioned for validations. In addition to the geometry, the second discomfiting factor included industrial specifications for the material composition of the different types of round-bar from which gear-sets were machined. To save waste in production, the round-bar from which these highly specific and expensive compounds were fabricated had diameters only marginally larger than the finished geometry. Securing the same steel material in appropriate dimensions proved problematic and ultimately impossible. A compromise was reached where LTU accepted a greater number of smaller diameter discs that were machined on both planes of the cylinder. This solution would provide a sufficient number of samples to complete the testing, but it also challenged the prototyping capabilities DPS and the single-piece production processes used to manufacture the discs. Since the particularities of DPS' manufacturing process had presented itself as an unavoidable agential cut that was part of conditioning the intra-action that generated the situated friction properties of the experimental lubricant, any deviation in manufacturing would increase the potential for dissimilar intra-action between DPS and Luleå.

For experimental results to provide industrially relevant meaning, multiple practical interactions between lubricants and complex component geometries must be translated into precise and controllable input parameters for the test-setup. LTU researchers Björling et al. (2011) have thoroughly described a method for tuning the lubricants. Tuning here means to molecularly manipulate lubricants' physical properties. Among numerous parameters, *entrainment speed*, *slide-to-roll ratio* and *oil temperature* are key input parameters for the types of friction analyses that LTU would conduct and from which *pressure-velocity* and *sheer-strength coefficients* could be derived. In the case considered here, entrainment speed was, calculation-wise, the most daunting of these parameters. *Oil temperature* is critical for its effects on the *viscosity* of hydraulic lubricants, but it can be easily measured. *Slide-to-roll ratio* on the other hand, is a derivative of *entrainment speed*. Calculating entrainment speeds – the velocities at which lubricants are transported between the gear-wheel and the gear-rim at *any* number of revolutions and at *every* normal vector of the wheel profile – required well-defined algorithms. These algorithms had been designed and validated in a previous DPS-LTU cooperation (Furustig et al. 2015a, 2015b) and could be re-purposed towards the proposed plan of action. But *executing* these algorithms required an *additional* set of inputs that were themselves a product of the precise function of the orbital motor as it was situated in the industrial test-rig.

In order to molecularly re-tune the lubricant, new measurements were required that observed the lubricant in relation to the material and micro-topological properties of the DPS gear sets. This meant that improvements of the lubricant demanded a reconfiguration of the highly specialized ball-on-disc test equipment so that its recordings were made under material conditions that were governed by the same situated manufacturing process that was responsible for the DPS gear sets. Ultimately this attention to the material conditions for the observable behavior that we tend to refer to as knowledge and knowhow, illustrates the operational importance of referential alignment. The careful orchestration of material conditions is the operator that makes possible that behavior in one situated practice resembles that which can be observed in another situated practice.

THE INDUSTRIAL TEST-RIG: MAKING TECHNOLOGY MARKETABLE

Test-rigs are central to technological development in DPS. They demonstrate the operational reliability and performance of any optimizations or new ideas associated with an orbital motor or its components and are the basis upon which real or simulated changes are empirically validated. Within the business of off highway mobile power solutions, meticulous empirical validation is a hall mark feature of the technological innovation. The test-rig at DPS serves a pivotal function within this scheme of innovation. By testing new solutions and ideas under strictly controlled conditions so that the toughest real-world use-conditions are emulated, the test-rig functions to ensure operational compatibility and reliability before any market release. The test-rig is designed to condition the intra-action between its components such that any imaginable intra-action in real world applications can be accounted for according to a multitude of test specifications. As such, an industrial test-rig must simulate the inputs and outputs of an orbital motor across its entire area of application. Figure 4 shows a hydraulic diagram of the test-rig from this collaboration, with brief descriptions of its principle components and their functions. For ease of communication, both inside and outside DPS, the diagram is constructed according to the guidelines of the European Fluid Power Committee (CETOP 2017) using standardized symbols (ISO 1219-1: 2012). All WF test-rigs have similar diagrams that allow DPS to clearly and concisely communicate functional relations between the principle hydraulic components comprising a test-rig to original equipment manufacturers. The heavily standardized testing and associated diagrams share characteristics with the notion of readymade science. Through established methods and evaluation criteria, the off highway mobile market can operate effectively insofar that its requirements and the solutions being offered fits the established standards. It needs to fit the railway system so to speak. The components of the diagram are typical, constituting elements of any off-highway mobile system, and can be (re)dimensioned and (re)assembled in virtually endless configurations. Consider figure 4: Load applied to an orbital motor (5.) through the work it performs (represented by the resistance motor 6.) will vary across applications. These variations can in turn effect the pressure settings of the different relief-valves (3.), as well as the dimensions and settings of the heat exchanger (7.), whose ability to cool the oil corelates to the amount of oil flowing to the tank (1.) without performing work – placing additional demands to the flow-capacity of the pump (2.)

that powers the orbital motor (5.) through the system of proportional valves (4.) that precisely actuates oil to the various components of the hydraulic system.

For Sustainalube to tune the lubricant, DPS needed to derive the entrainment speed and slide-to-roll ratio of the orbital gear-set, for *precisely* the area of the shell diagram (figure 2), at which the motor had been tested on the hydraulic test-rig (figure 4). In order to make the new lubricant technology relevant to the market, established standards and operational parameters formulated the questions that the test-rig was to answer on behalf of the lubricant. DPS needed to reduce the orbital motor's function to the basic working principles of its gear-set. Additionally, DPS would need to repeat

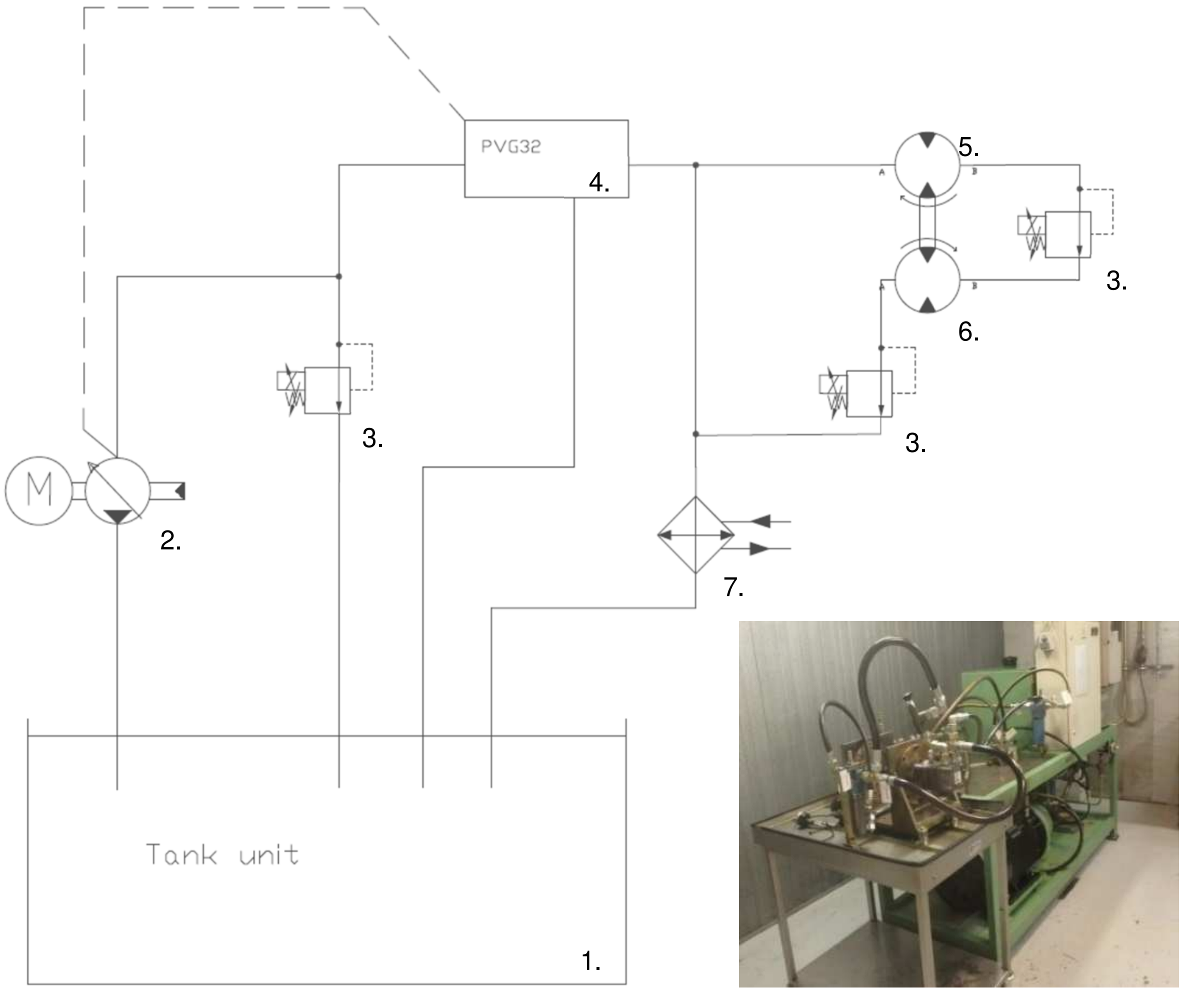

Figure 4: Hydraulic diagram of the case's test-rig, showing functional relations between its principle hydraulic components.

this process for numerous other test-points, until an ideal point within the functional area, where the new lubricant was most likely to perform well could be determined (i.e. the area where Sustainalube could showcase the operational reliability and performance of their product, see Bates and Juhl 2020, forthcoming: XX). To these ends DPS returned to the Furustig Model mentioned earlier, which was deployed to provide the parameters necessary for LTU to finally calculate the *pressure-velocity* and *sheer-strength* coefficients necessary for tuning the new lubricant.

On a knowledge-theoretical level, the case informs us about the intrinsic local conditions of material dynamics that underlie any form of technical and natural knowledge practice. While aggregated social systems such as markets, operate with established knowledge standards that can dictate requirements for new technologies, it is the material discursive practices that govern situated knowledge. Within the local context of Luleå University, Sustainalube was known for its friction properties that advanced on established standards. However, once the lubricant became subjected to industrial testing, the situated conditions at DPS revealed unexpected material wear. The situated knowledge practice around the test-rig at DPS, performed an agential cut that made unforeseen tribological properties of the new lubricant observable.

CONCLUSION

[Note that the conclusion is still being developed by the authors' and is not complete]

The industrial-academic collaboration of this case demonstrates how high-tech innovation and cutting-edge material science in one of Europe's best universities end up at the mercy of largely scientifically unknowable material intra-action that can only be managed by using the same exact same manufacturing knowhow. An important recognition from this observation is that science does not flow any more freely into society than society flows into science. If science wants to be relevant to industry it needs to ensure its applicability by aligning the conditions for its knowledge production with those of its target industries. Scientific knowledge and results are just as situated as any other practice of knowing. It is by recognizing the conditions that determine sciences' transferability that its limitations become knowable and its applicability can be realized. But applicability is not a result of science's own esoteric conditions, but rather of the successful alignment of shared conditions across situated knowledge practices where science is only one of many and has no a priory elevated status.

Haraway, Barad and Cartwright have in common that their philosophies of knowledges focus on the situated and contextual nature of knowledge practices. They propose understandings of how the local conditions knowledge as intrinsic ontological and epistemic features of situated knowledge practices. While dominant accounts of how scientific knowledge is produced examine how specificity and locality is lost for the sake of generating results that can travel across space and time (see Latour 1999), the accounts of Haraway, Cartwright and Barad enable us to maintain local specificity as a material condition for how we understand knowledge and thereby also the conditions for its applicability. We propose that this is especially important for studying the problematics of how knowledge claims are made in one setting and sought applied to another setting. For the study of science-industry collaborations, situated knowledge's locus around local material conditions contributes to a symmetrical analysis that avoids the tendency to emphasize formal scientific language over other forms of knowhow.

When observations deviate from the expected, the gaze of the observer must readjust to the material intra-action in order to observe the agential separability governed by the local material configuration. However, while local situated practices produce observations in each their way, the key to successful innovation science relies on aligning their material configurations in order to ensure that the observation produced in one setting can be reproduced within another setting.

BIBLIOGRAPHY

Bates, C.A., and Juhl, J. (2020, forthcoming). Staging referential alignment in industrial-academic collaboration. In C.Clausen, D. Vinck, S. Pedersen, and J. Dorland (eds.), *Staging Collaborative Design and Innovation: An Action-Oriented Participatory Approach.* Cheltenham: Edward Elgar Publishing.

Barad, K. (2003). Posthumanist performativity: Toward an understanding of how matter comes to matter. *Signs: Journal of women in culture and society*, 28(3), 801-831.

Björling, M., Larsson, R., Marklund, P., and Kassfeldt, E. (2011). Elastohydrodynamic lubrication friction mapping–the influence of lubricant, roughness, speed, and slide-to-roll ratio. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology,* 225(7), 671-681.

Bush, V. (1945). *Science, the Endless Frontier: A Report to the President*. Washington D.C.: US Government Printing Office.

Carney, S. (2006). University Governance In Denmark: From Democracy to Accountability?. *European Educational Research Journal*, 5(3-4), 221-233.

Cartwright, N. (1999). Models and The Limits Of Theory: Quantum Hamiltonians And The BCS Models Of Superconductivity. *Ideas In Context*, *52*, 241-281.

Cetina, K. K. (1999). *Epistemic Cultures: How The Sciences Make Knowledge*. Cambridge, MA: Harvard University Press.

Charlson, L. L. (1958). *U.S. Patent No. 2,821,171*. Washington, DC: U.S. Patent and Trademark Office.

Comité Européen des Transmissions Oléohydrauliques et Pneumatiques. (2017). *Education Recommendations*. Frankfurt am Main: CETOP Education General Secretariat.

Danfoss A/S. (2020). *Annual Report 2019.* Nordborg: Danfoss A/S.

Danfoss A/S (1973). *Motorer og tilbehør.* Nordborg: Danfoss A/S

Danfoss A/S. (2014). *Technical Information: Orbital Motors Type OML and OMM.* Nordborg: Danfoss A/S

Etzkowitz, H., and Leydesdorff, L. (2000). The Dynamics Of Innovation: From National Systems And “Mode 2” To A Triple Helix Of University–Industry–Government Relations. *Research policy*, 29(2), 109-123.

Furustig, J., Almqvist, A., Bates, C. A., Ennemark, P., and Larsson, R. (2015a). A Two Scale Mixed Lubrication Wearing-In Model, Applied to Hydraulic Motors. *Tribology International*, 90, 248-256.

Furustig, J., Larsson, R., Almqvist, A., Bates, C. A., and Ennemark, P. (2015b). A Wear Model for EHL Contacts in Gerotor Type Hydraulic Motors. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 229(2), 254-264.

Gamez-Montero, P. J., Codina, E., and Castilla, R. (2019). A Review of Gerotor Technology in Hydraulic Machines. *Energies*, 12(12), 2423.

Gibbons, M. (Ed.). (1994). *The New Production Of Knowledge: The Dynamics Of Science And Research In Contemporary Societies*. Thousand Oaks: Sage.

Haraway, D. (1991). *Simians, cyborgs, and women: The reinvention of nature*. London: Routledge.

International Organization for Standardization. (2012). *ISO 1219- 1:2012: Fluid Power Systems and Components—Graphical Symbols and Circuit Diagrams—Part 1: Graphical Symbols for Conventional Use and Data-Processing Applications*. Geneva: ISO.

Juhl, J. (2013). *Models in Action: Realising Abstractions (Doctoral* dissertation). Aalborg: Aalborg Universitetsforlag).

Juhl, J. (2016). Innovation Science: Between Models And Machines. *Engineering Studies,* 8(2), 116-139

Latour, B., and Woolgar, S. (1986). *Laboratory Life: The Construction of Scientific Facts* (Vol. 80). Princeton: Princeton University Press.

Latour, B. (1987). *Science In Action: How To Follow Scientists And Engineers Through Society*. Cambridge, MA: Harvard university press.

Latour, B. (1999) Circulating Reference: Sampling the Soil in the Amazon Forest. *Pandora's Hope: Essays on the Reality of Science Studies,* 24-79. Cambridge, MA: Harvard University Press.

Lugt, P. M., and Morales-Espejel, G. E. (2011). A review of elasto-hydrodynamic lubrication theory. *Tribology Transactions*, 54(3), 470-496.

Pfotenhauer, S. M., Juhl, J., and Aarden, E. (2019). Challenging the "deficit model" of innovation: Framing policy issues under the innovation imperative. *Research Policy*, 48(4), 895-904.

Pfotenhauer, S. M., and Juhl, J. (2017). Innovation and the political state: Beyond the myth of technologies and markets. In B. Godin, and

D. Vinck (eds.) *Critical Studies of Innovation*. Cheltenham: Edward Elgar Publishing.

Rodriguez, R., Warmerdam, J., and Triomphe, C. E. (2010). *The Lisbon Strategy 2000–2010: an analysis and evaluation of the methods used and results achieved, final report*. European Parliament, Directorate General for Internal Policies, Brussels, 277.

Rouse, J. (2002). *How scientific practices matter: Reclaiming philosophical naturalism*. Chicago: University of Chicago Press.

Shi, Y., Minami, I., Grahn, M., Björling, M., and Larsson, R. (2014). Boundary and elastohydrodynamic lubrication studies of glycerol aqueous solutions as green lubricants. *Tribology international*, 69, 39-45.

Strathern, M. (2000). The tyranny of transparency. *British educational research journal*, *26*(3), 309-321.

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