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How a project design becomes a macro-actor: Laboratory simulations in trials of strength between competing bridge designs, project budgets, and sustainability

Peter Skærbæk, Tim Neerup Themsen and Kjell Tryggestad

Abstract

Purpose: This paper shows how Bruno Latour's novel work and methodological approach can enrich management and organization studies, accounting, and science and technology studies on what it takes to redesign sustainable societal infrastructures. Latour's notions of trials of strength, macro-actor, and design as redesign are used in a case study to describe and analyse how the laboratory becomes decisive in negotiating the bridge design and project budget to the benefit of a more sustainable transport infrastructure.

Design/methodology/approach: Latour's notion of the detective-author is used to research and write a longitudinal qualitative case study that reconstructs the project processes and chain of related events by following the actors/actants.

Findings: The case analysis shows how a project design becomes an emerging powerful macro-actor through the mobilization of laboratory simulations and calculations. The role of the project budget changes; from a strong supporting role as input to a decision option in favour of a cheaper stayed bridge to a weak role as an output from a process of redesign supporting a much larger, costlier and more sustainable suspension bridge.

Originality: We use Latour's methodological approach to engage primarily in detailed process descriptions to go beyond the often-pointless call for further theory development and to rather account for what is at work in specific situations. Latour's notions of redesign as an outcome from trials of strength, we consider a useful approach to further our understanding since it also takes account of the distributed knowledge production that is integral to the actors' cognitions and recognitions. Relatedly, the specific Latourian notion of redesign opens up new avenues for researching *homo economicus* and the more or less powerful role accounting devices such as a project budget can play in valuing, supporting and/or undermining the design of sustainable societal infrastructures.

Keywords: Bruno Latour, trials of strength, macro-actor, design as redesign, project accounting and sustainability

1. Introduction

There are several seminal contributions from a social constructivist perspective that show how the design of technological objects is negotiated in interaction with experts and other humans and user groups (e.g. Bijker et al., 1987). In addition, within Science and Technology Studies (STS) there are seminal contributions from Actor-Network Theory (ANT), which adopts a less human-centred approach – a symmetrical approach – by also considering the active role of non-humans. Latour (1996) shows in the case of the failed urban transport project, Aramis, the role of inscriptions such as engineering design drawings, calculations, and prototypes in shaping project plans and outcomes. According to Latour (2009), design implies redesign; the project rarely progresses according to plan linearly and rationally. Latour's notion of trials of strength (Latour, 1988, 1990) captures the negotiations and struggles that decide the relative strength of competing knowledge claims. Relatedly, the notion of distributed cognition captures a key tenet in ANT; that what is going on in peoples' heads is secondary to the trials of strength that are going on in networks consisting of associations between people and things (Latour, 1986, 1987). The strengths (and weaknesses) of the associations are tested in the trials, and if successful a powerful non-human actor/actant such as a multinational corporation, what Callon and Latour (1981) also term a macro-actor, can emerge and stabilize.

Common to the above concepts is the argument laid out by Latour that there is nothing but trials: "There are only trials of strength, of weakness. Or more simply, there are only trials." (Latour, 1988, p. 158). We go along with Latour's approach by showing how a large Danish infrastructure project, the Great Belt fixed link, ended up in a trial of strength between two mutually excluding and competing bridge design options, which in turn challenged and changed the strength and role of the associated project budget. It is a chain of related events where associations between entities are constructed, tested, and eventually stabilized while other associations fail the test and become weaker until they eventually break. In brief, then, we follow Latour by considering trials of strength as a fundamental process of organizing. As also pointed out by scholars within Management and Organization Studies (MOS) and STS (e.g. Czarniawska, 2017; Doganova, 2020; Pollack and Clegg, 2023) the ANT approach is useful when seeking to uncover the organizing role of non-human actors in firms and in projects more specifically.

We take inspiration from selected works by Bruno Latour in order to research, describe and analyse the case of the Danish Great Belt project. We focus more specifically on the design and re-design of the East Bridge, which is the most capital-intensive part of the project. For more than 30 years a stayed bridge design had been planned. However, unexpectedly a newly established group of concerned Navigating officers intervened and objected to the plan. That intervention transformed into a trial of strength which in turn, unexpectedly came to involve laboratory experiments and new actors and events like ship accidents, oil pollution, and captains and pilots that had previously not been heard. The project ended up with a budget overrun of 51% and an extraordinarily large suspension bridge with the world's second-longest main span

when it opened for road traffic in 1998. By using Latour's work we seek to inquire into the chain of related events and to explain these unexpected outcomes.

We describe and analyse the development of the bridge design concepts and how these circulate within and outside the laboratory and link up with emerging devices and matters of concern such as the project cost budget, traffic safety, and care for the environment. Our case is well suited to demonstrate a key insight from Latour's work, that is, the power of the laboratory in 'raising the world' (Latour, 1983, 1990), and indeed, to even redesign a powerful low-cost budget calculating *homo economicus* (Latour, 2014) with its emphasis on a cheaper and unsustainable stayed bridge design.

In this way, our contribution should be understood as one that is using Latour's work to enrich MOS and ANT/STS research by providing a detailed account of what is at work in specific situations – notably we focus on the trials of strength – rather than a contribution that is aiming at 'theory development', which we consider to be less relevant if not pointless.

To summarize, we use Latour's work to 1. Research, describe and analyse the role of the project budget in trials of strength between competing designs and decision options and show how budget overruns unexpectedly contribute to project success and more sustainable project design and outcomes. 2. More specifically, we describe and analyse the role of the project budget as a valuation device that determines what is valuable. Relatedly we also consider the budget as a methodological entry point for studies of distributed cognition and redesign and as a mode of intervention for sustainability.

The paper is structured as follows: First, we provide a review and outline of some of Latour's key conceptual and methodological approaches that we use in our case research in order to reconstruct the actions and events of the project processes and events. Secondly, we carry out a case analysis that shows the trials of strength that provides for our explanations of the project's redesign- and budgeting processes and outcomes. We end with a discussion and conclusion with proposals for future research.

2. Bruno Latour's methodological approach

As noted by Czarniawska (2017) actor-network theory (ANT) as invented by Bruno Latour and Michel Callon is a methodological approach for doing field research to address the question of "How do things, people, and ideas become connected in larger units and remain so?" (p. 146). It is a symmetrical approach to ethnographic-inspired fieldwork and historical studies in the sense of keeping the question open as to who or what is the actor. Translated to our research, we ask who and what shapes the project processes and the related plans, goals, and outcomes – since we, following Latour – also consider that non-humans/things can play active and important roles. We describe and analyse the project processes for the most capital-intensive

parts of the Great Belt fixed link project, that is the East Bridge project.[1] We use Latour's (1988) notion of trials of strength to explain the project's resulting bridge design and project budget. We show how competing design concepts and associated cost estimates, i.e., inscriptions (Latour, 1987); emerge to become circulating references (Latour, 1999), and in turn, how they become associated with other people and things and negotiated during a protracted series of trials of strength, spanning more than 50 years. We focus on the decisive role of laboratory experiments and simulations in settling the controversy surrounding alternative bridge designs and their associated cost budgets.

Clegg (1989) notes the important contribution of Bruno Latour and Michel Callon in providing a novel and dynamic conceptualization of power. As further pointed out by Czarniawska and Hernes (2020), the perspective on power offered by Latour and ANT is not structural and static with an emphasis on people in powerful positions. Instead, the perspective is novel because it offers a dynamic perspective on power as an outcome of a translation process that links together previously unrelated entities consisting of both humans and non-humans. The conventional notion of power as residing in a social structure is replaced by a notion of power as an outcome of a process of organizing. The notion of the macro-actor (Callon and Latour, 1981) is perhaps the best-known ANT conceptualization of power (as outcome). The macro-actor is an actant composed of associations between human and non-human entities such as theories, models, and calculations. It is the powerful macro-actor that "bends space around itself, makes other elements depend upon itself and translates their will into a language of its own" (Callon & Latour, 1981, p. 286). The spokesperson speaks on behalf of the macro-actor, and as further noted by Czarniawska (2010) in her study of city projects, budget numbers do not speak for themselves but require a good spokesperson for the project to progress.

In our study, we consider the Great Belt East Bridge project as an emerging macro-actor that can grow in size over time by acquiring more resources such as more time, money, and new useful knowledge, that is, the creation of new associations between human and non-human entities. If translations are successful a small and ordinary micro-actor such as an engineer's design proposal for a suspension bridge, can grow to the size of a macro-actor. When successful, the macro-actor bends design decisions, funding/budgets, and laws to its requirements. Following Latour and Czarniawska (2017) we do not take the distinction between micro and macro (and meso in between) for granted. Instead, we consider such distinctions as outcomes in need of explanations. We use Latour's notion of trials of strength and focus on the specific project situation and decision of what to build, notably the decision to select among a set of competing bridge design options. Which design option is allowed to succeed and grow larger

[1] The parliament enacted a law for the fixed link project in 1987 and followed up with a decision to allocate funding which was further detailed in separate budget items in an appendix to the law from November 9, 1988. The three most capital-intensive items on the budget were, in million DKK: East Bridge (5.352), West Bridge (4.521), and East tunnel (3.851). In terms of outcomes, the National Audit Office filed a report about the actual costs for the budget items approximately eleven years later, in 1998: East Bridge (6.661), West Bridge (4.063), East Tunnel (5.5573).

and stronger to eventually become a macro-actor? Conversely, which competing design option eventually becomes weaker and is downsized into a micro-actor and failure? According to Callon and Latour (1981) the differences in size between a micro-actor and a macro-actor is an outcome in need of explanation. The authors consider that macro-actors also can be engaged in a trial of strength, implying a show-down between different and competing programs of action (Latour, 1991).

For Latour (e.g., 1983, 1987, 1988), the scientific laboratory with all its specialized equipment, scientific protocols, and expertise, can play a decisive role in the trials since it can produce new facts and truth claims that can ignite new controversies and trials as well as providing closure to existing ones. Inscription devices fuel the trials. Some specialized inscription devices can produce scientific readings that are visualized in the form of numbers and graphs on a screen or printed on a sheet of paper. A whole array or cascade of signs, inscription devices and visualizations can be involved in the form of images, drawings, numerical calculations, and texts that eventually are assembled and translated into factual results in a preliminary report. In the next sequence of events, the report can be translated into a scientific journal publication with a new truth claim put into circulation. With his notion of circulating reference, Latour (1999) summarizes the chain of transformations and translations and the inscription devices involved in scientific knowledge production; from the world of things, in his case soil sampling in the Amazonas, to the world of words/signs/inscriptions/reports, and back again.

In our case, we show how a maritime simulation laboratory returned with simulation results – in fact, a whole array of inscriptions and reports produced over many months – that together challenged the approved stayed bridge design. This brings us to Latour's (2009) notion of design as redesign. Latour considers the notion of a linear project where outcomes are according to initial project plans and design as a rationalistic fairy-tale told by the moderns. But we have never been modern (Latour, 1993). According to him, projects are better described and understood as processes that undergo redesign:

> ´Design' is never a process that begins from scratch: to design is always to redesign. There is always something that exists first as a given, as an issue, as a problem. (Latour, 2009, p. 4).

The problem and issue at hand are about if and eventually how to build a Great Belt East Bridge but as we will further explain, the proposed design solution with a stayed bridge, only generated a very prolonged series of new problems, issues, and matters of concerns implying yet further trials of strength regarding the bridge design and related matters of concern. Latour (2004) proposes the distinction 'matters of fact'/'matters of concern' to capture these emerging emotional-cognitive biases and their distributed networked character. We will use this

distinction in our case analysis since it both refers to a stable situation such as a scientific fact or an approved bridge design with a project budget that eventually becomes matters of concern.

In more recent developments of ANT, Doganova (2020) argues for 'valuation devices' as a useful analytic and methodological entry point for researchers interested in studying processes of economization and related matters of concern. Valuation devices such as a business model, a cost-benefit analysis, and we would like to add; accounting devices such as a balance sheet or a budget, are "scripts", following Akrich (1992). It is a vision and framework for action produced by inscriptions (Latour, 1986) through a process of inscribing into the device a social world of users and what is valuable for them. In Akrich's case of a lightning kit for users in rural Africa, the scriptors are engineers and designers in France. Doganova follows the work by Akrich (1992), Latour and Callon by also considering that the valuation device and script can be 'de-scribed' as it leaves the hands of designers and circulates into the hands of users. The outcome is highly uncertain; the users in the flesh may confirm the role and identity of the user inscribed into the device or problematize the script and submit it to trials. Doganova argues the case for ANT-based intervention through de-scription of valuation devices by accounting for the related trials, controversies and matters of concern. She notes that the expert language of economics is not useful since it excludes people from participating in debating such collective matters of concern. Latour (2014) raised a similar critique of economics' homo economicus, notably for its disregard of sustainability issues.

3. Research methodology

According to Latour, "A good text should trigger in a good reader this reaction: Please, more details, I want more details" (Latour, 2005, p.137). Our method is based on a longitudinal case study that reconstructs the chain of related events by following the actors/actants (Latour, 1987; Czarniawska, 2007). Taking further inspiration from Latour's (1996) detective-author in the Aramis case, we seek to reconstruct the chain of related events based on various empirical materials. The advantage of the metaphor of a 'detective' author is that it urges the researcher to collect the 'evidence' required to reconstruct the chain of related events leading to the 'deed'; in our case the 'killing' of a competing design alternative to the benefit of another one. Latour's (1988) notion of trials of strength provides us with the analytical lens through which we can understand and explain such related events and outcomes. More specifically our 'entry point' to the case research is a particular valuation device (Doganova, 2020), the project budget and how it changes its role and budget sum during the project processes.

The actants in our story are several; the cost accounting in the project budget, the engineering calculations and bridge designs, the coastal line, seabed, marine life, water currents, ship traffic, and especially large oil tankers and ship accidents that endanger the life of people and animals, peoples' emerging concerns, the laws and the politicians that enacts (new) laws, the Danish people, the sailors, media, bridges and tunnels, design visualizations of alternative bridge concepts, laboratory simulations and reports, to mention the most significant ones. We

research how these different entities emerge and become linked in unexpected ways, but also how new events and entities through a protracted series of trials both dissociate links and create new ones.

We have collected several types of documentation: budgets, and project reports, notably concerning the design simulations during the years 1989-90. In addition, we have collected letter exchanges between emerging concerned groups and members of the project organization, and between emerging concerned groups and representatives from the Danish parliament, ministries, and media. Last but not least, we have, like Latour (1996), also benefitted from an excellent and detailed description and analysis of the project events, i.e., Dr. Birgitte Munch's (1997) Actor-Network-Theory-based PhD thesis. In addition, we have benefitted from Professor Niels Jørgen Gimsing's (1984) historical review of the many projects and attempts to construct a fixed link over the Great Belt. As it turned out Gimsing was not only involved as an expert in 1977 in the last failed attempt (the project was closed in 1978 due to other governmental priorities), but soon after the publication of his book Gimsing also became a member of an advisory committee in 1987 for the next and successful attempt. We supplement with our empirical material, perhaps most notably through our access to the archives of letters and other documentation from some of the key actors involved in addressing the emerging sustainability concerns related to the bridge project. We also supplement with semi-structured interviews with key actors involved in the project. In contrast to Latour (1996), our case did not end as a failed project, so we have also supplemented it with additional empirical materials after the bridge opened to explain how it became successful. As we follow the project and bridge in real-time operations, we can also consider how it eventually could have turned out differently, as a disastrous failure. To paraphrase Latour (1988), the bridge was a 'tiered array of weaknesses' before it became stronger. Our task, then, is to explain how this process unfolded and what it implies in practical terms for how to construct sustainable societal infrastructures (rather than unsustainable disasters).

In Denmark, a public debate for more than 100 years gravitated around the question of constructing a bridge or fixed link across the Great Belt between the island of Zealand and Funen (Gimsing, 1984; Munch, 1997). Our case research focuses on the period between 1973 and 1998, i.e., when the bridge opened, and the controversies related to the exploration and selection of a design concept. We set out to reconstruct the chain of related actions and events. It is in style an attempt to create a storyline and to identify a plot of the study, by shadowing (Czarniawska, 2007) the involved actors, including a stream of documents and reports:

Figure 1: A stream of reports during the years 1990-91 from the design simulations at DMI.

In addition to the stream of simulation reports and books, we also negotiated access to the archive of the Navigating Officers Group, notably their numerous letters to the ministries and the parliament transport committee regarding their many concerns about the emerging Great Belt Bridge project. We also carried out interviews (for an overview, see Table 1).

Table 1: Interviews

#	Title	Role(s)	Notes
1	Professor 1	Professor at DTU and member in several committees advising to the parliament.	One taped phone interview and transcribed.
2	Professor 2	Professor at DTU and advising to COWI and member of committees advising to parliament.	One phone interview and email correspondence
3	Politician, Liberal Party	Member of parliaments Transportation Committee	One phone interview
4	Politician, Peoples Socialist Party	Member of parliaments Transportation Committee	One phone interview
5	Engineer, COWI	Risk analyst on the bridge design	One interview, transcribed 1,5 hours
6	Engineer, Danish Maritime Institute	In the lead of the simulations	One interview, transcribed, 1,5 hours. Physical visit to the laboratory and guided tour.
7	CEO, Danish Maritime Institute	CEO at time when the simulations were carried out.	A shorter telephone interview

8	Navigating Officer 1	Navigating Officers Group	Six phone interviews, one meeting.
9	Navigating Officer 2	Navigating Officers Group	One phone interview
10	Captain	Representative of Danish Shipping and member of the Captain's Group settled by parliament.	One taped interview, transcribed. 1 hour. Several informal conversations.

We interviewed two persons who led the laboratory simulations at the Danish Maritime Laboratory, which today operates under the name Force Technology. We paid an on-site visit to the laboratory, where the lead engineer took us on a guided tour showing us the simulator room where the simulations took place, see Figure 2. Even though the current simulation technologies are newer, in principle they work in the same way today. The engineer also showed us the water basin and wind tunnels where they carry out wind and water simulations. The image shows computer screens that can visualize the ship's movement as the hand provides steering input at the helm.

Figure 2: The maritime simulator at the Danish Maritime Laboratory

The interviewees were interviewed more than 25 years after the events and actions unfolded. Most of them could therefore not remember several things or even remember some actions and events wrongly. Therefore, we had the extra job of gathering many documents that would allow us to cross-check the information given. In addition, we also used the collected documents during interviews as a device to reconstruct memories of past events. We have sent a draft version of the paper to our respondents, and they have provided no objections to the case

account. One respondent provided a few suggestions for improvements, especially concerning the names of the groups and organizations involved.

4. Case narrative and analysis

In this section, we unfold our processual analysis of the trials of strength between the competing bridge designs and project budgets. We first provide a prelude to the earlier trials in the period 1965-1988. Next, we provide an analysis of the decisive trials of strength that culminated with laboratory simulations in 1990. The section ends with an epilogue.

Prelude: The first trials of strength regarding alternative bridge designs and costs – 1965-1988

During the years 1965-1973, three different design concepts emerged and were up for negotiation without any firm and positive conclusion about which bridge design to select. Two unresolved key issues became tensioned against each other during the trials; (i) from 1965, collision strength and safe passage for ships under the East Bridge, and (ii) from 1968, the cost of the East Bridge construction. The Stayed bridge design emerged as the stronger option since the Ministry of Traffic was not willing to pay the extra 200-300 million DKK for the larger and safer suspension bridge design and recommended instead the stayed bridge design consisting of three sections for sailing, each 325 meters wide (Gimsing, 1984; Munch, 1997). What was previously a controversy between competing design concepts with the safety issue for bridges and ships as the major concern now turned into a more complex trial that also involved a cost budget concern about economizing on the bridge design. The project process was halted shortly after the tendering due to the emergence of a national economic concern and new national priorities in the wake of an international oil crisis. In 1978, the archives with all the project documentation and plans were carefully sealed by the members of the project organization in anticipation of more supporting conditions. This is the end of the prelude that came to conclude that the stayed bridge design is the cheapest, and the most expensive bridge that Denmark as a country can afford.

The trials of strength before the laboratory simulations – 1988-1989

The project archive was reopened in 1983 and the work to develop the plans for a stayed bridge continued in the following years. As further explained by the design advisor COWI's risk analyst: "The point of departure was that the project was about a stayed bridge, because it is so much cheaper than a suspension bridge." The professor at DTU (Professor 2) and a representative from a project-appointed user group confirm this assessment and add that the stayed bridge option was considered economical and also aesthetic and visually unique. Eventually, the project work resulted in the parliament enacting a new law for the Great Belt fixed link in 1987, with a dedicated capital budget of 17.85 billion Danish kroner. The project

organization initiates work to develop the competition brief and tender approach for the project. During the fall of 1988, three navigators at Aarhus Harbor established the Navigating Officers Group in response to the newly enacted law and project. In January 1989, the Navigating Officers group, now consisting of a fourth member, wrote a report titled "The Great Belt Fixed Link - a project in crisis?" while questioning the realism of the project's traffic forecasts and economic calculations as being "too optimistic" (preface). The group even did their research on a reference class of similar projects and argued that these cases show: "That it is almost impossible to stay within the initial capital budget" (p. 20). The group concluded that the solution implies "large risks" in terms of keeping the project's time plan and cost budget. The group developed their concerns and arguments about the problematic aspects of the project in the following weeks. In February 1989 they wrote a summary in connection with a meeting with the parliament transport committee. In their written summary they have now added a new last bullet point of concern, titled "ship collision risks" (p. 2), which argues the case for high risks of ship collisions into the East Bridge and further asks the critical question whether: "The bridge is dimensioned to sustain a collision with even the largest ships?" (p. 2). This critical question was further addressed during the Navigating Officers group's meeting with the parliament transport committee.

In parallel developments, on 20 February 1989, The Navigating Officers group presented their arguments concerning the project's lack of sustainability at a press meeting in their own house, the 'Navigators' house'. According to them, the project will not only become a national and regional economic nightmare, but due to the small 780-meter span of the bridge it will also become an accident-prone infrastructure with ship collisions that put the lives of people and the environment, i.e., birds, fish, and marine biodiversity, at risk.

Their argument from the meeting was also made public a few days later on 28 February 1989 in the form of a written press meeting memo written by a journalist. At the meeting, the Navigating Officers group problematized the sustainability of the project's capital budget and argued for a significantly reduced project scope that only included rails on the west bridge and a tunnel for trains under the east side. This proposal, the group's spokesperson, Navigating Officer 1 argues, will help to cure the current project's "budget hangover" with cost increases from 10 billion to 18 billion Danish kroner. By dropping the East Bridge, the project cost will be reduced by seven billion Danish kroner. Another Navigating Officer points to the fact that during the last eight years, there have been six recorded incidents of ships sailing into lighthouses anchored on the seabed. That officer then goes on to question whether the project organization the Great Belt, Ltd. has designed the bridge to take ship sailing accidents into account: "Is the East bridge dimensioned to sustain a collision with the largest 200.000 tons ships?" (Quoted from Press meeting memo 28 February 1989, pp. 3-4, by journalist Hans Trier). The press memo is soon sent to the Technical Director of the Danish Railways, DSB. As Navigating Officer 1 explains, the project comprises more issues and stakes than the economy and the safe passage for ships.

> "We raised the issue that the narrow span of the stayed bridge would imply a risk not just for a collapse of the bridge and what that entails, but also that they risk creating what could become the greatest pollution accident in the world. If a 100,000-tonne ship collides with the bridge and ends up leaking oil." (Navigating Officer 1).

The emergence of this environmental issue is confirmed by the MP of the Peoples Socialist Party who says that the risk of pollution became an important issue. She further says that she engaged herself in several discussions with engineers about the probability that a ship would collide with the bridge. Professor 1 also emphasized how, after the intervention of the Navigating Officers group, several issues were moved to the agenda concerning the bridge design.

Already at the press meeting on 20 February 1989, Navigating Officer 1 addressed the way the project organization so far had managed the "environmental crisis" […] by eradicating the environmental organizations by counter-reports" (Press memo report, p. 1). During the meeting, the Navigating officers also addressed their concerns about a future with increased CO2 emissions due to the road traffic over the East Bridge along with the risk of ships colliding with the bridge. According to them, it would be better not to build the East bridge for the above reasons, but also because it will cost much more than parliament has approved.

After the Navigating Officers Group's problematization of the bridge design and its cost budget, the project organization decided to explore the question further through simulations at the Danish Maritime Laboratory, involving three Pilots. In addition, a formally appointed Captains Group' was established to advise project management about sailing conditions. This group was having its first meeting on 13 April 1989. COWI, which was involved as a design advisor when the previous project attempt halted in 1978, is now tasked with the key responsibility of designing the East Bridge. COWI developed two alternative design options for the East Bridge for further consideration: either a stayed bridge or a suspension bridge. The challenge of designing a bridge with a span that was wide enough to reduce the risk of a ship collision, yet strong enough to withstand a collision, is still unresolved. The design challenge has also become much larger because ships have become much larger during the recent years. This uncertainty needed to be addressed when solving the design task. In addition to COWI, the project organization also hires a professor at DTU (Professor 2) to advise on the design task. During a conversation, professor 2 asked COWI's risk analyst: "What is the difference in quality between a stayed bridge with a little span and a suspension bridge with a large span? We need to inquire into this question, but how?" The risk analyst further explains:

> "[the professor] and the CEO at COWI were both members of the board at the Danish Maritime Laboratory and then we were thinking that their simulator could be useful to illuminate this question. And so, it became an activity." (Risk analyst at COWI).

This proved to be the end of a long struggle by the Navigating Officers Group to challenge the stayed bridge design and project budget. However, the trial continues by other means, that is, through a detour in the form of a series of laboratory simulations. What is still at stake is whether the narrower stayed bridge with its smaller budget is the most viable solution, or if the competing option with a larger, costlier and more sustainable suspension bridge should be the preferred choice.

The decisive trials of strength during the laboratory simulations – 1989-1990

When SBF had decided to carry out simulations at DMI COWI contacted three Danish pilots to participate in the simulations. As Munck (1997, p. 293) describes this encounter:

> "When they (COWI) called, I said that I could come in and talk to them. I knew nothing about it. They said: We need 2-3 people to find out about this. I think it was their view at that time that no more (pilots) were needed, and that we could do it right away here and now." (Quote from a Pilot in Munch, 1997, p. 293, translated to English).

Two series of laboratory simulations were conducted in the summer and late fall of 1989. During the simulation processes, the pilots became clearer about their task, but also more concerned about how the results from the simulations could be used or abused. Navigating Officer 1, the spokesperson for the Navigating Officers Group, explains that pilots' concerns resulted in a leak of their "Collision" report to him and the press:

> "The pilots were very critical about their participation in the simulations. One of the reasons was that the pilots were not represented in the Captains Group. That group discussed and analyzed the simulations, but there were no pilots in the group. Also, they feared that they would be misused by the GBB to just legitimize what they had already decided to do." (Navigating Officer 1)

The preliminary results from the first simulations with the pilots during the summer are summarized in a COWI report titled "Ship collision study", with a 'Postscript' dated 12 October

1989. Several simulations of different bridge designs with different types and lengths are conducted, including different sizes of ships and variable sailing conditions such as traffic, water currents, wind- speed and directions. The findings are included in the report along with information about a new and still ongoing series of simulations:

> "A series of simulations are ongoing and will further illuminate the sailing conditions under different bridge spans; 900m. 1200 m., 1400m., 1600 m., and 1800 m. and 2*800 m.» (p.7). This is due to the first simulation finding that the bridge span« "should be at least 1400 meters (Pilots Report, 1989)."

The report, along with the pilots involved in the simulations, concludes that a stayed bridge with a 780-meter span is too small; a much longer suspension bridge with a span of at least 1400 meters is recommended. The conclusion was further reinforced by references to a previous study, the CAP report from 1977/1978, about the risks for ships' collisions with bridges in the Great Belt and Dr Fujii's domain theory and its equation for the manoeuvre space a ship required when passing under a bridge.[2] For example, a ship with a length of 200 meters will, according to the theory, require a 1480-meter bridge length (2x3,2+1*200 ship length) or "approximately 1500 meters" (p. 4). The domain theory and its equation purify the report's simulation results and conclusions by adding the strength of science in the trials. Simultaneously, the report is weakening the feasibility of the competing alternative based on a 780-meter long-stayed bridge design: "As far as the stayed bridge is concerned, two ships cannot pass each other without transgressing each other domains […] which is unrealistic" (p. 4).

It appears that due to the laboratory simulations the stayed bridge design option that for so many years had mustered the support making it the most realistic alternative was about to become more unrealistic and unreal. As professor 1 further explains:

> "The stayed bridge option was unrealistic from a practical and legal point of view because the only safe passage would be for one ship to wait while the other sailed under the bridge. But that kind of restriction on the navigation of ships would violate international laws and sea regulations." (Professor 1).

[2] Professor 2 explains in a separate e-mail exchange with one of the authors (dated 26 May 2023) that s/he was involved in writing a report in the late 1970s together with two prominent professors in economics where they warned against building a stayed bridge.

Finally, the report considers in some detail the risk of collisions between ships and between a ship and the bridge. Again, the 780-meter-long stayed bridge design is problematized, even a longer 1200-meter design is problematized:

> "The sailing conditions will be worsened [compared to the current situation without a bridge] to such a degree that the risk for a collision will become very high" (p. 6).

The report refers to known models for calculating the collision risks and concludes that a design with bridge spans between 1400 meters and 1600 meters significantly reduces the risks of collisions down to the current levels without a bridge. These risk calculations were done by COWI's risk analyst and further verified by Professor 2. By adding these design-collusion risk calculations to the report's simulation results, the cheaper 780-meter stayed bridge design appears even more unrealistic and unreal. Since 1978, about 11 years of support for that alternative from the Danish Maritime Authority, Military Maritime Unit, and the Ministry of Traffic appears to be undermined.

On October 13, 1989, one day after the report concluding the first series of simulations was finished, a project meeting with the project director and a formally appointed user group with captains, i.e., the 'Captain's Group' were held. At this meeting, it became clear to all concerned that the project director and the representatives from the Captains Group had developed very diverging interests concerning the competing design options. The captains wanted a suspension bridge because it allowed for a longer span compared to the stayed bridge design. To them, a longer span translated into more space for navigating the ship under variable conditions with changing wind directions and speed, water currents, sights, and traffic and therefore a more secure sailing under the bridge. The project director, however, did not agree at all with the Captain's Group and the meeting developed into a trial between two competing design options. As one of the representatives of the Shipping Association from the Captain's Group, recalls it:

> "We had a long and heated meeting. It was us, with a maritime background that was very interested in the length of the bridge span and the ship's alignment with the bridge. It was a matter of feeling comfort while passing the bridge, considering alignment, the north-western wind, and the direction and speed over the seabed. We could not approve the planned stayed bridge design because the span was too narrow. Instead, we wanted a longer span, between 1200 and 1600 meters." (Captain).

The project director replied to the members of the Captain's Group, that h/e could not understand why half a kilometre bridge span would not be enough and explained that the group's preferred design option would incur more costs. As he recalled, the project director asked him directly as a representative for the shipping association: "Will the Danish shipping association pay for the extra costs related to a suspension bridge design?" The representative answered no, and the meeting ended with a provisional compromise. To settle the entangled controversy over more or less costly, secure, and sustainable design options, additional design simulations were required that took into account captains' interests in bridge spans with a length of up to 1600 meters.

The "Collision study" report from October 12, 1989, recommended postponing the final design decision to simulate an even longer 1800-meter suspension bridge span. The controversy between the project director and the members of the Captain's Group during their meeting on October 13, 1989, added strength to this request for what the additional second series of simulations should be about.

The "factual report" from the second series of simulations during the fall of 1989 further substantiates the conclusion from the "Collision study" about the need for a bridge design with a span that was at least 1400 meters. The simulations concerned a stayed bridge with a 780-meter span and a suspension bridge design with a 1416-meter span. See Figure 3.

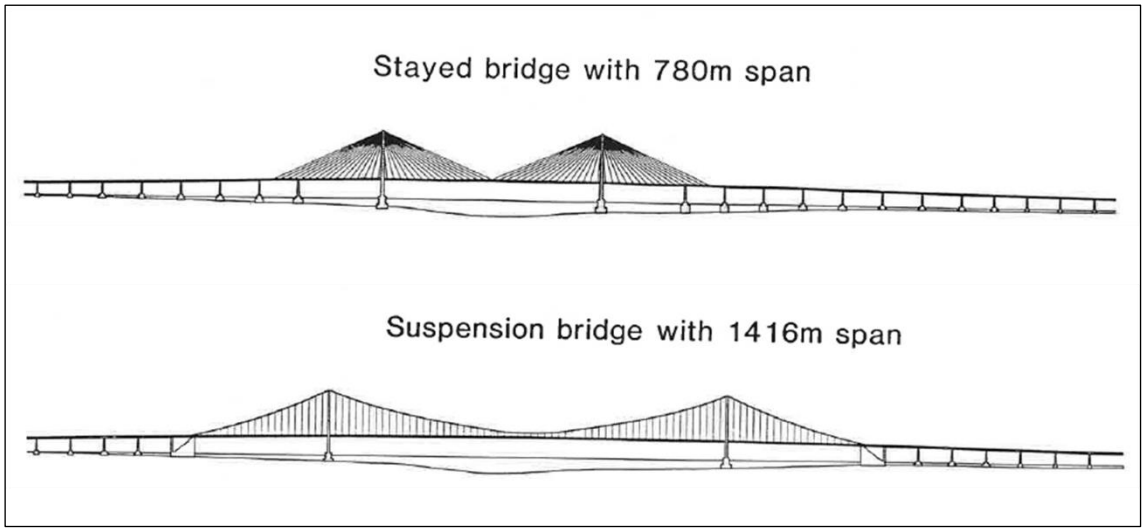

Figure 3: The two bridge designs (Danish Maritime Institute, 1990)

However, at the time the Parliament Traffic Committee still did not know which bridge would be constructed. Would it be a smaller stayed bridge with higher environmental risks, or a larger and safer suspension bridge, yet with larger economic risks? The MP of the Liberal Party was active in the Traffic Committee and was of the view that the management of the Great Belt Ltd. did not believe that the simulations would change anything: "They felt to be quite certain. They did not believe the simulations would change anything." Further, the MP

addressed the Minister of Traffic directly in the parliament on December 6th, 1989 (Ingeniøren, 8 December 1989) by asking about what bridge is to be built, and what the additional costs of building a larger suspension bridge will be if that is chosen.

In subsequent developments, on 6 February 1990, and only a few weeks before the conclusion of the third and last simulation, a high-level meeting in the project organization the Great Belt Ltd. took place at the Danish Maritime Laboratory. It was a decision meeting about the design concept for the East Bridge. Eventually, it could also become a historic decision if the meeting could conclude the now several decades-long design decision process; to either opt for the cheaper stayed bridge design with a narrower span or the more expensive suspension bridge design with a much longer span. Professor 1 was invited to hold a keynote before the decision. In addition, the CEO of COWI, the project's lead designer, and advisor to the project. were also invited to hold a keynote. Both presented their views on the preferred design concept and reached the same conclusion: the project should construct a suspension bridge and its span should be approximately "1700 meters" (Munch, 1997, p. 278). As it eventually turned out, the final decision maker and project owner, the Ministry of Traffic followed the decision and recommendation from the project meeting.

An enduring series of matters of concern turned into a matter of fact. In fact, the actual suspension bridge constructed ended up with a 1624-meter span. As Professor 1 further explained (in an interview on 4 April 2023), the actual length of the last 24 meters was an effect of the length of each of the sections constructed, "since each section should be as long as possible" the sections just added up to make the bridge span 1624 meters long.

A third and final series of laboratory simulations is scheduled for March 1990. At this point, the Navigating Officers group keeps problematizing the project management and the Ministry of Traffic for their long commitment and all the resources spent on the 780-meter-stayed bridge. The group mobilised the recent design decision to construct the costlier suspension bridge as a new context for asking critical questions about how the project will account for all the costs and investments in developing the stayed bridge concept. In addition, the Navigating Officers group problematize the current budget plan and estimates for lagging behind the new realities with a new design decision and project context. The group circulates the reference to the book by Professor Gimsing (1984) about his recommendation of a suspension bridge design between 1200-1500 meters in a series of letters to the Ministry of Traffic (dated 19 March 1990, and with reminders and request for a reply; 15 April, 6 May, 28 May, all letters with a copy to the Traffic committee in the Parliament):

> "Gimsing writes in his book, citation: "That the most favourable span for a suspension bridge will be between 1200 and 1500 meters. However, investigations have shown that a bridge with a large suspension bridge span will become more expensive than a stayed bridge with the 780 m. span." [Further more]:

> "This information is known to the Great Belt Company, however, *they still calculate the budget based on a stayed bridge with only a span of 780 m.* Experts we have consulted estimate a suspension bridge to be 1 billion DKK more expensive." (Letter from Navigating Officers group to Minister of Traffic dated 19 March 1990, p. 1. Emphasis added).

In effect, the Navigating Officers group provides a close reading of the cost estimate that is inscribed into the budget as a matter of fact and then turn that estimate into a matter of concern by *de-scribing* that at least 1 billion Danish kroner is omitted, notably the additional costs related to the design decision to opt for the larger suspension bridge. In addition, there were the costs of the many years of design work leading up to that decision. The Ministry of Traffic responded to the series of letters and critical questions from the group in a letter from June 1, 1990. The Minister closed the debate without going along with their distinction between 'pre-project' design and planning costs, and project costs. According to the minister the design costs for the stayed bridge was outside the budget since it did not belong to tendering costs to be included in the project budget. With respect to the cost budget, there could not be any budget overrun since there were no contracts in place. The design decision in favour of the costlier suspension bridge generated a new project context associated with strong emotions, not only within the top project management team but also among professional designers, advisors, ministries and public agencies that had invested so much effort in exploring and supporting the losing alternative. For example, the risk analyst at COWI explained that:

> "At the time COWI collaborated on the stayed bridge with a German company […]. However, when the stayed bridge design was abandoned several employees at COWI became angry, they scowled at me, all that we had done was [according to them] probably wrong." (Risk Analyst).

In addition to the internal disagreements in COWI, there were also other reactions among involved authorities, as the risk analyst explains. The simulations made a difference:

> "[...]the Military Maritime Unit and the Danish Maritime Authority who approved the stayed bridge in 1978 now got busy explaining themselves, so they say,« there were no simulations back then." (Risk analyst).

The Ministry of Traffic was not happy with the suspension bridge design, since its larger size was so strongly associated with additional costs. In 1991, during a meeting between the Navigating Officers group and the Minister of Traffic, one of its members recalls what Minister

Kaj Ikast said: “It is because of you that the span of the bridge became so large.” (Interview with Navigating Officer 2).

The new design decision is estimated to add approximately 1.368 million Danish kroner to the previously approved budget of 4.399 million from 1988. As the National Audit Office (1998) further explained:

> “From November 1990 to the March 1991 budget there was an increase for the East Bridge by 1,368.2 million DKK. The change is caused by a tender result for a suspension bridge with a span of 1624 meters, which was higher than the one in the budget-defined amount. The budget was based on a stayed bridge with a span of 780 meters. In the budget further adjustments have taken place due to a longer construction period” (Rigsrevisionen, 1998 p. 16).

It appears that the inscription of a cheap stayed bridge into a low-cost budget can also be de-scribed, but it will require the intervention of a group of dedicated readers, like the Navigating Officers, to provide a de-scription of the budget that can account for and include the other valuable things such as a sustainable bridge design. The investments and costs of design, simulations and redesign are relevant examples to that point. The design decision in favour of the larger, costlier, and more sustainable suspension bridge marks the end of these trials, but also the conclusion of who and what is becoming the macro-actor in this large infrastructure project. It is not individual humans or a group of humans that become the macro-actor, but a long chain of human and non-human associations that are tested, of which some associations become stronger at the expense of those that become weaker. The low-cost budget inscribed with the stayed bridge becomes weaker and has to pay. The successful suspension bridge design can mobilize additional financial resources to be built. A renegotiated budget inscribed with a larger sum is decided by the parliament. The geography of the Great Belt is about to be reshaped, making space for the larger suspension bridge with fewer pylons and more space for the safe and legal passage of ships. It is the macro-actor that succeeds in bending interrelated spaces, i.e., the economic space of a revised cost budget the interrelated physical spaces of the bridge design and the space for ship navigation under the bridge. Even time is bent, since the redesigned and larger suspension bridge is granted more time for construction and ships are allowed free passage under it without (illegal) waiting and queening time. The size of the associations making up the macro-actor is an outcome of the trials of strength; how the project design of a suspension bridge becomes a macro-actor and the failure of the losing alternative is an outcome of the trials of strength. This ends our analysis of the trials of strength between competing bridge designs and their associated budgets.

Epilogue

The East Bridge opened on June 14, 1998. Although the bridge was close to being hit by a 27,000-ton ship in 2021, it is still standing tall and is playing its faithful role in making the Great Belt Fixed Link a successful sustainable transportation infrastructure. The revenues from traffic have exceeded even the most optimistic expectations; from 3.7 million vehicles during the first year of operations to 13.25 million vehicles today. The fixed link has become a 'cash cow' and it funds other public projects. By 2022, which is the year that was originally decided to be the time for the final repayment of the debt, there is still a 19.1 billion DKK debt to be settled from the project. The government expects the debts to be repaid by 2034. This implies that the public cannot cross the bridge for free, presumably until then (Ministry of Transport, 8 April 2022. Letter to Transport Committee).

5. Discussion

In the introduction, we outlined two contributions that we will address below:

Our first contribution is geared towards the usefulness of Latour's twin notions of trials of strength and design as redesign. As our case analysis shows, the bridge design is, as Latour rightly emphasizes, a negotiated outcome from trials of strength involving processes of redesign. Relatedly, also the project budget becomes redesigned as an outcome of the trials of strength.

In his later work, Latour expressed concerns, even great frustrations, with the economic man of economics – *homo economicus* – since he considered that nature and the earth have become subsumed under the unsustainable epoch of the Anthropocene, with *homo economicus* at its helm. But there is still hope, what has been designed can be redesigned. In Latour's (2014) own words "No feature of *Homo oeconomicus* is very old: its subjectivity, its calculative skills, its cognitive abilities, its sets of passions and interests are recent historical creations just as much as the "goods" they are supposed to buy, to sell and to enjoy, and just as much as the vast urban and industrial infrastructure in which they have learned to survive. What has been made so quickly can be unmade just as quickly. What has been designed may be redesigned." (p.12).

Our case and analysis speak to Latour's concerns. For many years the cheaper stayed bridge was considered the strongest option. The estimated cost of the stayed bridge is also inscribed into the budget via the law enacted by the parliament. What is inscribed is the value of economizing on costs – it is a *homo economicus* that is inscribed into the budget. The budget becomes a script and program of action to economize on the costs. It is a value that for many years determines the design process in favour of the cheaper stayed bridge option.

The inscription makes the budget play a powerful role as a 'valuation device' (Doganova, 2020) in subsequent design work. It mobilizes engineers, designers, and advisors to focus on refining the cheaper stayed-bridge design. If the budget was allowed to play this powerful role in the final design decision, this project would most likely have ended with a stayed bridge. The

outcome is contingent on the other emerging matters of concern that go beyond and challenge the budget concern and its inscribed value of economizing on the costs. It is an extraordinary challenge to challenge *homo economicus* and its value of a low-cost option because all concerned people understand that value while only a few engineers and scientists understand what it takes to design a sustainable bridge. The group of concerned navigators became powerful spokespersons for the latter while speaking against the cheaper unsustainable stayed bridge, which paved the way for the decisive trial of strength in the simulation laboratory.

In effect, the budget becomes weaker as it must adapt to a design issue about sustainability that becomes stronger and more real due to the laboratory trials. The role of the budget changes; from a strong role as an input to a design process supporting the cheaper stayed bridge option to become transformed into a weaker role as an output from a re-design process supporting the larger and costlier suspension bridge option. The budget of *homo economicus* is no longer providing the support and steering input at the helm of this project process because its inscribed value of economizing on costs has been overwritten as the budget is re-inscribed with another value of a more sustainable bridge design. The identity and power of *homo economicus* is transformed as an integral part of the trials of strength. *Homo economicus'* low-cost program of action is not sustainable, it becomes weaker as the budget adapts to the more sustainable suspension bridge design. Latour (2014) is to the point, what is designed can also be redesigned and *homo economicus, this macro-actor,* is no exception. In our case, it appears that it requires a well-equipped maritime laboratory to challenge and downsize such a calculative creature when it is equipped with a matter-of-fact low-cost budget.

There is some comfort to this story since it shows that it is possible to take sustainability and important matters of concern into account in a cost budget. But this unexpected outcome is also a reminder, that it requires much knowledge work and effort to challenge the powerful inscriptions of *homo economicus*. Methodologically, it requires that the MOS researcher follows the actors as design inscriptions are challenged through detailed de-scriptions of bridge designs and related budgets. MOS research and ANT/STS have since long developed an interest in design but there is a lack of studies that relates design processes to economic calculations such as cost budgets and more generally, to the calculative devices and skills that constitute the identity of a *homo economicus*. If nothing more, we hope that our Latourian study helps to remedy this gap. There is still hope, as Latour rightly emphasizes, that it is possible to accomplish a reversal of roles, identities and outcomes about what matters matter. The difference in size and design between the successful macro-actor and the losing alternative is an outcome of the trials of strength.

Following Doganova's (2020) ANT-inspired work on valuation devices, we consider the budget as a valuation device and as a useful methodological entry point for studies of distributed cognition and re-design and as a mode of intervention for sustainability. As our case analysis shows, it requires extraordinary investments in new devices for valuation and intervention, most notably; the laboratory simulations and the development of new sustainable bridge designs, to challenge and redesign a strong budget inscription with a focus on economizing on the costs. Conversely, without these interventions, the low-cost budget inscription could have remained strong, and perhaps even become stronger, if supported by other devices that emphasize the integrity and value of keeping the cost budget. As documented by Themsen and Skærbæk, (2018), risk management devices with a focus on the risk of going over the budget can unexpectedly participate in causing unfortunate outcomes in large societal infrastructure projects. In our case analysis, we have shown that other risk management devices also can establish a strong and supporting association to redesign and in turn, challenge the integrity of the low-cost budget. Jacobsen et al. (2002) use Latour's (2009) notion of redesign to account for the organization and outcomes of architectural competitions and call for more research on the connection between design and finance. There is a need for more research on accounting as valuation devices and modes of intervention in MOS and project research more specifically.

6. Conclusion

To conclude, the success of the Great Belt suspension Bridge is a lesson on the power of new knowledge resources as they are produced during trials of strength of which the laboratory simulations proved to be decisive. To succeed and overcome the powerful budget inscription of a low-cost stayed bridge design requires the mobilization of additional resources such as the simulations in a Danish Maritime Laboratory. The specialist equipment, inscriptions, and simulations that visualize the ships and their required space for safe navigation are integral to the dynamics of cognitions and recognitions amongst the agencies that different, larger, and more sustainable bridge designs are required. These processes of knowledge production are not confined to cognitive mental processes inside the head of an individual human (or group of humans). Instead, these knowledge processes are captured by notions such as 'visualization and cognition' in the vein of Latour (1986) since they illuminate the distributed and active roles of visualization devices; a budget estimate on a sheet of paper that circulates, a computer screen that visualizes the ship's movement as the hand provide steering input at the helm of a simulation laboratory, the reports that circulates and that summarize the findings, to mention but a few. As these inscriptions and visualizations circulate, they become integral to a distributed and negotiated character of knowledge production and recognition. Our case account and findings are no exception, we could not have accomplished this case account of the actors and the chain of related events without taking inspiration from the Latourian way by following document traces and the inscriptions as they circulate, in a similar way to the trail-sniffing detective-author-invented by Bruno Latour (1996). To ANT researchers like us, there is a

puzzle to be solved each time a new case is opened, and Bruno Latour offers the qualitative- and processual methodological tools to research the case and its unfolding chain of related events. The work by Bruno Latour is still an unmatched source of inspiration due to his novel methodological-processual approaches. Surely, there are many important cases to research, and we call for more Latour-inspired case-based field research to account for what is at work in specific situations. More specifically, we take up Latour's (2014) more recent challenge by calling for more MOS research about how non-human identities such as homo economicus and associated devices such as a low-cost budget and a project design are negotiated and redesigned during trials of strength and how they perform together and/or separately to make sustainability a more or less strong organizational and societal matter of concern.

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