INFRASTRUCTURAL SYSTEMS AND TECHNICAL CHANGE
- Learning from the establishment of a water- and wastewater system and the electrification of a railway line in a Nordic climate at the turn of the 19th century

by

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Introduction

In recent years, partly due to the emerging global warming problem, interest in petroleum, wind power, fishing, shipping and other activities in the far north has increased. This has spurred increased research efforts in fields such as construction and infrastructural systems in cold climates. Most of this research is today conducted by engineers,[1] many of them associated with one of the public and/or industrial research centers that are specialized in the field and are located in the northern parts of the world. This article addresses some important questions related to establishing infrastructures in cold climates in the past, in particular how those involved in the establishment of infrastructure in cold climates and in remote places managed, before any actual research in the field existed and prior to the general infrastructural technology was fully established, to construct working systems.

In the early 20th century, one such far-north and still rather remote and unexploited region was the northernmost parts of Sweden, close by the Arctic Circle. Due to its growing importance as a mining and timber region in the end of the 19th century, followed by a steady growing population, buildings and infrastructures had to be built for both industrial and socioeconomic purposes. In this article, we study the processes of technology choices made by engineers and other decision-makers in connection to two largely contemporary infrastructural projects in this dveloping northernmost region of Sweden at the turn of the 19th century, i.e., the establishment of the Luleå town water- and wastewater system[2] and the electrification of the so-called Riksgränsbanan Railway (the Frontier Railway). These infrastructural systems are different both when it comes to the services delivered and to how they function in general.

[1] See, for example, Sand (2008) and Nielsen (2000).
[2] At the local level, water- and wastewater systems are dependent on each other and are thereby in this coherence regarded as one connected system.

However, what was common for their build-up and operation was the mutual challenge of the typically harsh climate of the region. An important point of departure of this study is also that historical investigations of infrastructural systems, not the least empirical studies at the micro-level of technical challenges, should be of interest not only to those involved in establishing infrastructures in cold climate but also to the contemporary sustainability debate on policy design and implementation.

Illustration nr 1 (The Arctic Circle, CIA World Factbook)

Learning (for sustainability) from infrastructural systems in the past

Jonsson et al. (2000) point out that at least two circumstances speak for infrastructural systems having a strategic role to play in the strive towards a more sustainable societal development: 1) they contribute to environmental strain by the way they work; and 2) they promote a societal development that has come to involve extensive consumption of goods, not the least personal travel and energy use. In changing infrastructural systems towards a more sustainable direction, the authors argue that incremental changes, such as altered relative prices between different kinds of energy carriers, will not be enough. What is needed in addition are system improvements[3], social synergies[4], and/or, social innovations[5], where the key to a successful development above all is to be found among the latter two. Van Vliet et al. (2005) in turn express it as a requirement (for the production of more sustainable systems of utility provision) of a transformation of collective social and material arrangements.[6] They also stress the advantages of viewing infrastructural change through the lenses of transition theories, i.e., as a multidimensional process taking place across a number of levels.[7] However, they point out that this would require further scrutiny at the empirical level. Kaijser (2003) in

[3] This implies making a system (or type of system) more effective (one at the time) (Jonsson et al., 2000, p. 6).
[4] More effective production of the system-services by coordination of different systems (Jonsson et al., 2000, p. 6).
[5] What is implied is here are the changed ways households consider their needs and handle livelihood on the one hand, and the altered forms of organization within the spheres of production and distribution on the other (Jonsson et al., 2000, p. 64).
[6] They further define four aspects of environmental renewal in utility systems (service differentiation; scales of provision; autonomous networks; demand-side management), and outline the forms of socio-technical change that these imply. These changes include multiple products and services and improved choice (e.g. green electricity and waste recycling); increased technical and institutional fragmentation and new modes of access (e.g. local water systems and composting); mainstream disconnection and local reintegration of technologies and practices (e.g. eco-homes); reconnection of supply-demand management and improved efficiency (e.g. storage systems and efficiency devices) (van Vliet et al., 2005, p. 36).
[7] This would show the "variety of routes possible, each moving at different speeds and each exhibiting different degrees of path dependency, lock-in and irreversibility," (van Vliet et al., 2005, p. 36).

turn argue that the understanding of the developments of infrastructural systems in the past is a prerequisite for redirecting them towards sustainability. The task of an historian is not to define what kind of changes (of the infrastructural systems) are desirable for the future, Kaijser continues, but instead to try to provide lessons of the general character of such processes.

Kaijser (1994; 2003) provides several general lessons of historical studies on infrastructural systems, such as the strong influence of transportation systems on settlement patterns and the socio-technical character of the systems implying the alteration of system culture and institutional conditions if lasting changes of the system are to be achieved. Furthermore, infrastructural systems go through different phases (establishment, expansion, and, stagnation), where each phase is associated with different problems to solve and different roles for policy design and implementation. Kaijser also points out that historical studies of infrastructural systems can illustrate the critical importance of the interplay between various types of such systems; both in the sense that competition among systems fulfilling the same function can constitute a major driving force in the development of new systems or cause the decline of others, and that infrastructural systems sometimes play a complementary role to each other, producing synergistic effects (such as railways and telegraph lines).[8] In this paper we emphasize the importance of empirical micro-level studies of infrastructural change in mature systems in the past, i.e., a focus on the expansion/stagnation or growth/consolidation phases in terms of Kaijser (1994; 2003) and Hughes (1983; 1987), respectively. This parallels a challenge that many cities and municipalities[9] face today, namely to initiate and achieve complex socio-technical changes of mature infrastructural systems.

Scholars have over the last few decades observed some shortcomings of the so-called LTS tradition in the historical study of socio-technical systems, such as a focus on first time establishments of systems rather than mature systems, and a bias toward examining successful system builders and their desire to control and expand these systems. This in turn has often promoted a biased, top-down perspective on system development.[10] The relative lack of

[8] See especially Kaijser (1994), pp. 75-95; respectively Kaijser (2004), pp. 172-178.

[9] Sweden has a tradition of strong local autonomy in combination with a demand on municipalities to implement national policies and to formulate local strategies accordingly (Gustavsson, A, 1996, *Kommunal självstyrelse*. Stockholm: SNS. *Kommunallagen*, SFS 1991:900). This is not the least true when it comes to making society more sustainable.

[10] For a summary of the critique directed towards the LTS-approach, see, for instance, Jonsson (2006) p. 37f., and Summerton (1998) pp. 33-35.

examples in the literature of comparisons among different kinds of systems has also been pointed out as a shortcoming, since such comparisons can give us a better understanding of the specific characteristics of individual systems as well as of the common characteristics of all infrastructural systems.[11] In this article we address some of the above shortcomings by comparing two different and rather mature systems: both the water- and wastewater system and the railway system were mature infrastructures at the beginning of the 20th century. Water- and wastewater systems had however never before been established so far north, at least not in Sweden, and the Frontier Railway was the first major section of a Swedish state-owned railway to be subject to the radical invention of electrification. Moreover, we primarily adopt a bottom-up perspective so as to capture the implications of local prerequisites, such as climate, on the technology choices related to the respective infrastructures. With a micro-level approach to the infrastructural establishment, rather than the traditional systems building approach, it is useful to supplement the frame of reference of this study with the economic-historian Nathan Rosenberg's analysis of the process of technical change at the micro level.

Technical knowledge and change

In order to understand technical change at the micro level, Rosenberg suggests a focus on how information, new as well as old, becomes embedded in new technology, and the presence of incomplete information is essential in his analysis of technical change.[12] As the development of new technology requires new information, achieving technical change can be a very costly process. As a consequence much of the development activities become devoted to efforts to improve existing technologies rather than to introduce new technology, and present activities are powerfully shaped by technical knowledge inherited from the past which creates a path dependency of the development.[13] This is not the least true when it comes to production forms with high capital intensity, such as most infrastructural systems.[14]

Due to diverse prerequisites in the past and thus unique compositions of inherited technical knowledge for different investors in technology, technical change seldom constitutes a choice between given and well-identified technical solutions. Instead, they are characterized by a search for technical knowledge that can be transformed into unique technical solutions. This

[11] Kaijser (2003), p 155.
[12] Rosenberg (1994), p. 11.
[13] Rosenberg (1994) p.14.
[14] About path-dependency and technical change, see also Arthur (1989).

illustrates the often blurred distinction between technology choice on the one hand and technical development on the other.[15]

An important component of Rosenberg's analysis is also the distinction between scientific and technical knowledge. He states that the body of presently available scientific knowledge imposes certain *constraints* on what is technically possible and also, by the same token, permits a range of technical alternatives to be taken up within the frontiers imposed by that knowledge.[16] According to Rosenberg, technical progress is however a result of a multiplicity of factors, where the guidance of science is only *one* among many other important variables.[17] An essential element for all types of innovations, following Rosenberg's reasoning, is an activity which implies various kinds of uncertainties.[18] The inability to predict its outcome, and the inability to predict which development path is most effective in order to reach a certain goal, makes it very difficult to plan the activity. For this reason technical development is typically based on gradual, sequential decisions made at the micro level, and is strongly connected to the local context.[19]

Rosenberg's reasoning is based on the individual firm but is applicable to any organization with limited economic assets aiming for technical change or adoption. This could be a municipality or regional/national organization (together with consultants) wishing to establish infrastructural systems. It could also be the local/national management of already established infrastructural systems aiming to change a system. In the following empirical section of the article, we learn that whereas the town of Luleå was almost completely dependent on the knowledge of consultants, whose activities were powerfully shaped by scientific and technical knowledge inherited from the past, the Swedish National Railways Board both was in the possession of knowledge of central importance to the project and, at the same time, was deeply dependent on the knowledge of other actors. Both cases further illustrate the often blurred distinction between technology choice and technical development, as well as the typically strong connection to the local context.

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[15] Rosenberg (1994).
[16] Rosenberg (1994) chapter 1.
[17] Rosenberg (1994) pp. 13, 202.
[18] Rosenberg (1994) p. 93.
[19] See also Hughes, T.P (1983).

Technical changes in infrastructural systems: two historical cases

This paper explores and compares technical changes in connection to the establishment of Luleå town water- and wastewater system and the electrification of the Frontier Railway (Riksgränsbanan Railway) in the socio-economically simmering northernmost region of Sweden at the turn of the 19th century. The study of the Luleå town water- and wastewater system is mainly based on minutes and other documents of the local City council, Health committee, Building committee, Water mine committee and Financial department of Luleå town from the 1880s to the first decade of the 20th century (Luleå city archive), and further on documents kept at the archive of SWECO AB[20] (Stockholm).[21] The sources used regarding the electrification of the Frontier Railway are mainly correspondence, reports and contracts compiled and kept at the National Railways Board and its Bureau for electric traction (Swedish National Archives[22]). Other sources used are official documents from the Swedish government and the Swedish parliament.

Luleå was rather late in establishing a water- and wastewater system a few years into the 20th century – the city of Stockholm established its water- and wastewater system between the 1850s and the 1870s and most other Swedish towns did so in the last two decades of the 19th century and the few first of the 20th century. The system that was established in Luleå was thus relatively mature; on the other hand it was the most northernmost (latitude 65) water- and wastewater system to ever have been established in Sweden and probably the world, which would come to mean some additional challenges to those involved in the establishment apart from the challenges naturally connected to technical change-processes of this caliber. The establishment further took place at a time of intensive development phases within bacteriology and drilling technology, which came to influence the local implementation process in a major way.

The Frontier Railway was in turn the northernmost railway line in Sweden and the first major section of a state-owned railway to be electrified. This major and (in Sweden) first-time upgrading of the railway system of course meant radical changes to the otherwise mature railway system, and indeed major challenges of both technical and organizational character

[20] AB Water constructions office (AB Vattenbyggnadsbyrån), which was involved in the establishment of Luleå water and wastewater system (see below), is today included in SWECO.
[21] For a closer description of sources, see Söderholm (2007).
[22] Riksarkivet, branch Arninge, Stockholm.

for the State Railways (SJ) and the associated consulting companies. On top of that, the northernmost situation of the Frontier Railway, as for Luleå water- and wastewater system, with the typically harsh climate of the region, meant additional major challenges of a technical character.

The establishment of the Luleå town water- and wastewater system

The decision to invest in a public water- and wastewater system was taken in the city council of Luleå in September 1904. A number of factors explain why the decision took place at that time, including the existence of a number of critical institutions making it possible to take the decision as well as the existence of a need for the decision to take place. With the 'Municipal reform' (Kommunalreformen) of 1862 the municipality had become its own legal entity with regulation and taxation power and with the right to, for example, obtain loans. With the 'Health care act' (Hälsovårdsstadgan) of 1874, towns further had become required to establish Health committees that were obliged to see to the supply of potable water and to otherwise report to the national 'Medicinal board' (Medicinalstyrelsen). The growing interest in health care issues and in identifying solutions to sanity problems can be explained by the severe cholera epidemics in many Swedish towns in the 1850s and 1860s. The choice of solutions were in turn based on prevailing poisoning- and contamination theories where diseases were thought to originate from foul sources (from refuse piles to water bodies) by smells and vapours. In parallel to the high-points of the poisoning- and contamination theories during the 1880s, bacteriology and knowledge about the pathogenic bacteria became more widespread.[23] The theories (and their change) are mirrored in discussions about establishments of water- and wastewater systems and did influence their design (see below).[24] With the 'Building Act' (Byggnadsstadgan) of 1874 towns further had become obliged to establish Building committees whereby they gained an institution which could organize and operate public building-projects such as water- and wastewater systems.

Five years before the city council took the decision to invest in a water- and wastewater system, it had applied for, and obtained the right to, a bond loan of 1.6 million SEK in 1899 (about 8 million EUR in today's money value) for the realization of a number of purposes, such as the establishment of a new harbour, a city hall, a customs house, a school house and a market hall, as well as for the reorganisation of the fire- and police department and for an

[23] Drangert, Nelson and Nilsson (2002), p. 174.
[24] See also Melosi (2000), p. 12ff; and Nelson and Rogers (1994), p. 35.

expanded power station. The biggest expense category applied for, i.e., 550 000 SEK (about 2.8 million EUR in today's money-value), was for the establishment of a water- and wastewater system. These significant investments were in large motivated by the fact that the population had doubled in only a few years, to about 10 000 in the year of 1900, due largely to the increased iron ore production in the region and the thereby increased importance of Luleå as a shipping town (a railway had been established between Luleå and the most important iron ore mines in the region in the late 1880s). When the town applied for the bond loan in 1899, the city council had already been discussing the water- and wastewater question for years, i.e., especially the establishment of a wastewater system.

Wastewater - versus - water

The question of establishing a wastewater system was, as early as in the mid 1880s, first raised within the city council of Luleå (it thus took over two decades from when the question was initiated until the construction process started). In many other towns at this time, the primary motive had been to construct water systems in order to improve fire safety and hygiene, as well as the status of the town. The wastewater systems did in these contexts take the character of a necessity as the increased amount of water (through the water systems) meant more wastewater to handle. In Luleå, however, the primary interest lay in establishing a wastewater system. This we know by the number of applications that were submitted to the city council by private individuals during the last couple of decades of the 19th century, concerning the wish to construct drainpipes at shorter distances at the center of the town. Some of the applicants insisted that the town finance the construction of the suggested drainpipes, others were prepared to finance them privately (but needed the right to use public land). As early as the late 1880s, the city council assigned an engineer within the local building committee to set up a plan for a wastewater system for the town. A corresponding plan for a water system was not set up until many years later (1898), in spite of the fact that the town had been exposed to a devastating fire in June 1887.

The position of the city center, on a peninsula in the middle of the Lule River, probably had an influence on this situation. At the same time as the situation on a peninsula meant an ever crowded and of course worsened hygienic situation when the population doubled in the 1890s, it also meant that wherever you were situated in the city center, you were never more than a couple of minutes away from the rather large and clean river where fire extinguishers could be filled up and water picked up for household need. Through documents of the public health committee of Luleå, we however know that the town experienced the (mis-) handling of excrement and waste as severe sanitary problems at the turn of the 19^{th} century. The documents give witness of neglected backyards and badly handled privy cleaning of excrement, slops and waste, which the health service supervisor mainly explained by the lack of a wastewater system. The harsh climate helps explain the neglected backyards in that cold temperatures and large amounts of snow, concealed and thus for both smell and sight totally hid excrement, slops and waste during the long winter months. However, what is hidden under snow comes forward at thaw, and at thaw, not only what is hidden under snow needs to be taken care of, but also the large amounts of snow itself, now turning into melt water. The climate thus also helps explaining why the population of Luleå wanted to establish a wastewater system prior to a water supply system (whereas the opposite way around was more common in other towns).

Illustration nr 2 (Central Luleå in the spring of 1903, i.e., a few years before the establishment of a wastewater system, Luleå city archive)

Choice of consultant and choice of water supply

At the time of the construction of the Luleå water and wastewater system, questions concerning the choice of suitable materials and diameter of the pipes could be answered relatively easily due to some decades of Swedish experiences in the field. The choices of water supply, depth of pipes (i.e., of their situation in ground), the hauling of water and the construction of the reservoir however constituted central challenges in the establishment of the water- and wastewater system. Quite a few of these challenges originated from new scientific findings and technical achievements within, for instance, bacteriology, hydrology, chemistry and within the technologies of drilling and water-hauling, achievements which among other things actualized the question of using subsoil-water instead of previously only surface-water as water supply. As most of the uncertainties at the time thus had to do with the establishment of water systems as opposed to wastewater systems, we will mainly focus on technical changes related to the establishment of the Luleå water system.

Engineer Forsgren was a member of the local building committee and the one who had been assigned by the city council in the late 1880s to present a plan for a wastewater system covering the central parts of the town. In 1896 he presented his plan and calculated the costs as 126 000 SEK (about 735 000 EUR in today's money-value). We do not really know why it took that long for Forsgren to complete his plan, but it is probably a result of both the complexity of the assignment and the fact that the building committee of Luleå was heavily occupied with other investments as well (see above). Forsgren did however manage to deliver a rather sophisticated plan (see also below) given that he, as far as we know, did not posses past experience with establishing wastewater systems. In the plan, the dimensions of the combined pipes (both storm- and sewage water) are calculated according to water-quantity at thaw and taking into account maximum possible fall of rain and or snow. Forsgren established that the sewage water would be "of little significance" compared to this other water. He further identified the pipes that were "necessary" to drain the central parts of the town.

After the wastewater plan had been presented, the question of establishing a water system in parallel to the wastewater system was raised in the city council. In the autumn of 1896 the council consulted lieutenant Wilhelm Hansen, responsible for the Stockholm water system, in relation to putting together a plan for a water system for the town of Luleå. Lieutenant Hansen sent word from Stockholm that he was willing to do so. The building contractor of the town, Mr Smith, shortly thereafter in letter to Hansen suggested that the Lule River, at a spot just outside the outermost point of the peninsula on which the central town was situated, ought to be appropriate as water supply. Hansen was however not satisfied with the idea as he found an imminent risk that the river was, or soon would be, polluted at that spot by wastewater from the north and west parts of the town, and at times of inward current (from the Gulf of Bothnia), also from other parts of the town. As a basis of his assessment, Hansen used a map – he had never yet visited the remotely and northernmost situated (about 1000 km north of Stockholm) town of Luleå. Was there not instead, Hansen wondered, some "underground water-carrying layers" near the town? Building contractor Smith however abounded in his opinion in the following letter to Hansen, and asserted it as "natural" to use the "perchance most water-rich and clean river in Sweden" as the water-supply, as it passed just by the town, referring to "this never-ending source". And Smith went on to say that he did not know of any bigger underground water-carrying layers nearby. When it otherwise came to the quality of the water in the existing wells of the town, he enclosed a statement by Paul Hellstrom at the 'Chemically plant-biological institution' in Luleå, which stated that from a chemical standpoint it was well exceeded by the quality of the river-water.

Illustration nr 3 (View over the western district of Luleå and Lule river in 1893, Luleå city archive)

Hansen however continued to try and dissuade the council from the use of the river nearby as a water supply as; “one nowadays consider sewage water from human dwellings to be of greatest danger [for the suitability of drinking-water], also in much diluted condition, [as] one single bacteria [has been shown to] act as seed of disease”. When it comes to the above statement by Hellstrom, Hansen in turn establishes that it “of course” is of little use in these matters, as a bacteriological in contrast to chemical examination “clearly” would confirm the contamination of the river water. He concluded by suggesting that drilling-tests for subsoil water ought to be arranged, and he pointed out the advantages of subsoil water over surface water. The former did not need to be filtered, it was not exposed to external contamination and had an even temperature over the year.

Later, in the autumn of 1897, drilling-tests for subsoil-water were carried out in the centre and outskirts of the town under the command of one of Hansen’s assistants. A sufficiently ample deposit was however not found until one was located rather far up north of the town. As it would mean a fairly big investment for the town to lead water from a deposit that far away and as it went against the grain to give up the river-alternative, the city council was not content with the result. Thus, Hellström, at the ‘Chemically plant-biological institution’, was again assigned but this time to do a year-long bacteriological examination of the river-water. The investigation, which was finished in the early autumn of 1899, showed that the river-water most of the time was of particularly good quality, both chemically as well as from a bacteriological standpoint. The waste of the town did however contaminate the river at thaw and ice-opening. This, together with an increased salt-content in the harbour during winter, meant according to Hellström, that river-water if used as water-supply should be taken rather far up north of the town. The findings of Hellström, i.e., of the climate/season-related negative effects on the river-water near by town (concentrated contamination), probably helps explain why the city council at this time seems to have given up the idea of using the river as a water supply source. Hansen’s rather expensive suggestion to use subsoil-water far up north of the town was not seen as a good alternative. Thus, at this time, the city council engaged yet another consultant for the establishment of the Luleå water- and wastewater system, engineer

Johan Gustaf Richert, the then recent founder of the 'AE Water constructions office' (AB Vattenbyggnadsbyrån) in Stockholm.

Richert was just finishing a project in Sweden's second largest town, Gothenburg, where he, in cooperation with German hydrologists, used streams of subsoil water supplied by surface water, by artificial infiltration, from the Gotha River (Göta älv). The method had been developed in Germany and thus brought to Sweden by Richert, and was implemented for the first time in Gothenburg in 1898. For Luleå, Richert suggested a water system dimensioned for a population of 15 000 (at the time, the population was about half of that, however, fast growing). To reach enough pressure in the pipes for fire fighting and other purposes, he suggested a constant water access of 1200 cubic metres per day and a 'high-reservoir' of 1000 cubic metres in a mountain just north of the town. He further suggested that water to be taken from a bay north up the river, not far from the subsoil-deposit found by Hansen's assistant, where river-water was to be artificially infiltrated through the river-bank and thereafter hauled through drilled wells. With such a procedure, Richert pointed out, water would be gained that was; "absolutely free from every contamination from the sewage water of the town and at the same time independent of the saltiness from the Gulf of Bothnia". Richert thus in a way came to unite the two former water-supply alternatives, i.e., of using river water versus subsoil-water.

The realization of Richert's plan would of course mean big investments for the town, not the least to lead water that far and to have to haul it up from wells. Richert however pointed out that the more common method, of purifying river-water in artificial basins, and so avoiding the wells, was not really an option in this case as the basins would have to be covered due to the harsh climate, plus the water-temperature not be as constant as it would by his plan, or the purification as effective. Considering the potential of situating the water supply nearer town, Richert in turn referred to the maximum filter speed formulated by the bacteriologist Robert Koch and established that such a situation indeed would demand far-reaching precautions including filtration.

After yet a couple of additional, however unsuccessful, drilling-tests for subsoil water on the peninsula of the central town in the summer of 1901, to see if it was possible to conduct artificial infiltration at closer distance to town, the city council after yet a few years after that (in September 1904) decided to establish a water- and wastewater system in line with

Richert's suggestions. Richert had also on request come up with a plan for a wastewater system, which largely came to follow the original plan by the local engineer Forsgren from 1896, which in turn indicates that Forsgrens' plan was rather sophisticated from start.

The harsh climate came to influence the technology choices in other ways beyond excluding options of choice when it came to water-purifying methods. The pipes were for example placed as deep as at 2.3 (water) and 2.5 (wastewater) meters depth, and were at some places enclosed by fine sand due to the severe ground frost. This choice was probably partly based on information inherited from private experiences in the local context of Luleå from constructing drainpipes over shorter distances. The situation and connection (to the remaining net) of the fire plugs were also connected with uncertainties due to the climate. Richert wanted to situate the fire plugs in the roadway (however not in the middle of it), just above the main pipes instead of in the sidewalk in order to avoid the risk for the side pipes to freeze. He had recent experiences of the latter from the town of Helsingborg, located in the very south of Sweden (at latitude 56). A local engineer however pointed out to Richert that such a situation of the fire plugs would mean great inconvenience for the road traffic in the winter whereas pits would have to be held open around them in the snow. In the end, the fire plugs were situated the way Richert wanted, i.e., in the roadway. However, special frames with wooden lids were developed to be placed over the fire plugs at winter in order to lessen the inconvenience to road-traffic of open pits in the roadways. Feeders were further to the greatest possible extent connected to the fire plugs in order to achieve regular turnover of the water and so avoid freezing.

In the autumn of 1906, two years after it was decided in the city council, a water- and wastewater distribution system with water supply and artificial infiltration at a bay north of the town and a 'high-reservoir' in a mountain in between, was established in the town of Luleå.

Illustration nr 4 (Blasting works before stretching of water main to the high reservoir at the hill of Mjölkudden in 1905, Luleå city archive)

The Frontier Railway as a sociotechnical primary system

The Frontier Railway (Riksgränsbanan) is the northernmost railway line in Sweden, located far above the Arctic Circle and covering a distance of almost 130 kilometres (about 81 miles) between the municipality of Kiruna and Riksgränsen (the national border between Sweden and Norway). The railway is in addition a part of the Iron Ore Line (Malmbanan), which connects the iron ore mines in Kiruna and Gällivare/Malmberget with the shipping ports in Narvik, Norway, and Luleå, Sweden. The first part of the Iron Ore Line was completed in 1888, connecting Gällivare with Luleå. The last part, the Frontier Railway, was fully operational from November 1902. However, it was not formally opened until the following summer as king Oscar II did not want to travel that far north during the dark and cold winter.

From the beginning steam locomotives hauled the ore trains on the Frontier Railway but due to reasons discussed below this was coming to an end in 1915. The railway was electrified over the period 1910-1915, and it thereby became Sweden's first state-owned railway line in regular traffic to use electricity as motive power. Furthermore, the Frontier Railway constituted a part of a technical mega-system in this part of the country (Hansson, 1994, 1998). This mega-system consists of the Iron Ore Line, the iron ore mines in Kiruna and Malmberget, the fortresses and garrison in Boden, the ironworks in Luleå, and the shipping harbours in both Luleå and Narvik. All these facilities are connected and interdependent with the main objective to refine, transport/ship and protect the iron ore mined in the northernmost part of Sweden (Lapland's mining districts).

The Frontier Railway can also be defined as a co-operating cluster of several minor technical systems. It is possible to distinguish four different technical systems that are required in order to operate a railway: telecommunication system, signaling system, track system, and electric power system. Even though each one of these systems is able to function separately they all become interdependent when their joint function converts into being in support of railway transportation. These four systems are in that sense secondary but when operating together they might be described as a technical primary system. The thorough system change that the railway as a consequence underwent during the electrification thus becomes an example of a radical invention within a mature system, where really only one of the minor systems changed radically, i.e., the power system. The other three systems were only subject to minor alterations as they had to adjust to the electrification. However, a technical system consists of more than just its technical components and by also including all the people who, for instance, build, invest, work, and make use of the system it can be identified as a sociotechnical system (Hughes 1983; Kaijser 1986, 1994). The Frontier Railway can thus be defined as a sociotechnical primary system.

Reasons behind Sweden's first major railway electrification

There were several reasons why Swedish officials wanted to electrify the railway system at the beginning of the twentieth century. One main reason was the desire to reduce the dependency on imported coal. Pit coal was without comparison the most important power source and responsible for about 99 percent and 97 percent of the power supply for railroads and ships, respectively. Swedish industry and agriculture used approximately 65 percent coal as fuel for steam boilers and machines while coal also accounted for nearly 25 percent of household heating. Swedish coal could not compete with imported coal as it had a lower thermal value and was very brittle, making it difficult to transport and store. The unfortunate combination of a large dependency and a lack of domestic alternatives meant that the cost for imported coal became very high and could amount to as much as 15 percent of total imports.[25] Another reason to reduce the import of coal was a matter of national security. If the import of coal was disturbed due to an international conflict or domestic disturbances abroad (e.g., a strike) this could seriously affect Sweden's transportation system and industry with further consequences for trade and the wellbeing of its citizens.

Another prerequisite to the electrification of the Frontier Railway was a number of innovations regarding electric technology which had been made since the beginning of the twentieth century. The development of the three phase system and new motor constructions made it possible to use higher voltages. The effect losses from high-tension transmission lines were also reduced, which meant that distantly placed waterfalls could be used as power source for heavy-duty railway traffic. Furthermore, this also meant that there existed an alternative to coal in Sweden; the waterfalls. Already in 1899 a national committee was inspecting state-owned waterfalls to decide where hydroelectric power plants could be constructed. They concluded that there were several waterfalls suitable and some of them were situated near the

[25] The cost fluctuated very much every year and depended upon the actual amount of imported coal but also on altered price formations. As an example, during the year 1900 3 million tons of coal were imported with a total value of approximately 80 million SEK (about 374 million EUR in today's money-value), corresponding to roughly 15 percent of the total import. Ten years later 4.2 million tons were imported at a total cost of 56 million SEK (about 237 million EUR in today's money-value), about 8.5 percent of total imports that year.

Iron Ore Line. In addition, there were several examples of electric traction used at smaller railways both in Sweden and in other countries. After the Swedish National Railways Board had conducted experiments on test tracks in Stockholm 1905-1907, and concluded that there were no hindrances to an electrification of the Swedish railway system, only one question remained: what railway line should be electrified first?

The railway chosen by the Swedish National Railways Board was the Frontier Railway even though an in-house memorandum to the Cabinet Minister and Head of the Royal Ministry of Public Administration stated a number of objections to this choice. The memo stressed the harsh local climate and the fear that the geographical position of the railway could become troublesome during the construction due to the long distance from Stockholm. On the other hand, one reason in favor of an electrification of the Frontier Railway was its location. If the new technical system could function so far up in the north it would most likely work everywhere else in the country. Another reason in favor of the Frontier Railway was the type of traffic running there. It was mainly made up of heavy-duty iron-ore trains and operational disturbances would not be as problematic as it would on a more diversified railway with a larger proportion of post- and passenger traffic. Yet another reason was financial as this railway-line was one of the most profitable lines in the country and a new freight contract with the mining companies involved stipulated a fixed price for every ton transported. This meant that decreased costs of transportation would render a greater profit to the state. However, the main reason why the choice fell upon the Frontier Railway was because the Swedish State entered as a part-owner in the mining company LKAB during 1907 and they soon decided to increase the amount of iron ore to be exported, from 1 500 000 tons in 1908 to 3 850 000 tons in 1918. In order to meet these new demands the Iron Ore Line had to be upgraded and improved. New steam locomotives had to be bought, the ventilation in tunnels had to be improved, and some sections had to be constructed with double tracks. This implied large investments in a system the decision-makers did not believe would pay off in the long run. The double tracks alone would cost about 3 000 000 SEK (about 12.7 million EUR in today's money-value) and take more than three years to construct. However, there was an alternative - to venture forward with a radical new technology: electric traction.

Illustration nr 5 (Map over the stretching of the Iron Ore Line, CIA World Factbook)

After an extensive bidding procedure lasting more than a year, the National Railways Board selected the German company Siemens Schuckert Werke together with the Swedish company ASEA as contractors for the electrification of the Frontier Railway. One initial stipulation regarding the project was that the companies involved should defray the expense of the entire railway electrification while the Swedish State would be responsible for the construction of the hydroelectric power plant. On April 4, 1910 a government bill was introduced regarding the electrification of Riksgränsbanan Railway. The Parliament voted in favor of spending 21 500 000 SEK (about 91 million EUR in today's money-value) to the project. The bill required that only 35 percent of the total expenditure could be used to pay for foreign deliveries, and that all locomotives had to be built in Sweden.

A trailblazing project in the far north

The electrification of the Riksgränsbanan railway was in many ways a trailblazing project where new technologies were developed and launched on a rather troublesome railway line, considering the harsh climate and its geographical location in the wilderness of northern Sweden. Swedish engineers working at the National Swedish Railways Board's Bureau of electrical power were regularly sent on study tours to electrical companies and railways in Germany, England, Holland and North America to gain knowledge about the most recent discoveries and innovations in the field. Letters with inquiries about technical matters were also sent to colleagues, both in Sweden and abroad. This way of obtaining knowledge about new technology seems to have been a rather common and important way of technical diffusion during this period.

As part of electrifying the Frontier Railway, a number of technical problems had to be solved regarding the rolling stock and the electrical system, including overhead contact wires, insulators, poles, high tension regulating transformers, and buildings among other things.[26] All components had to withstand extremely cold and snowy conditions. Siemens had, for instance, requested information from the National Railways Board about the temperature along the railway. According to measurements done by four meteorological stations in the area the temperature could drop to -40º C during the winter with an average temperature of

[26] Matters regarding the high voltage transmission line and the hydroelectric power plant built in Porjus have been omitted from this paper, even though it constitutes a vital part of the system. For further information about the building of the Porjus power plant, see Hansson (1994).

about -13ºC at Riksgränsen. In addition, the winter lasted for about seven months, October-April. During this time large amounts of snow fell and this could influence the traffic on the Frontier Railway. There had been disturbances due to heavy snowfall every year since the line had been operational. If the winter was snowy and cold the opposite could be said about the summer which could be very warm, especially in July. The summer also brought other things with it like the midnight sun and millions of mosquitoes terrorizing everyone in sight, both man and animal. They proved to be a real disturbance for many in the work force during the electrification process.

During the winter of 1908, a 1 kilometer long overhead contact system was constructed by the Bureau of electrical power near Vassijaure station. This experimental line was built before the political decision was made to electrify the Frontier Railway and can serve as an early example of the importance by which the Bureau of electrical power regarded the climatologically effects upon the system. A lot of experiences were gained during the experiments on the first test tracks in Stockholm 1905-1907 but the construction of an overhead contact system along the Frontier Railway was supposed to provide additional knowledge about both the toughness of the materials used and the capacity of the system. The poles used were made of wood and impregnated with a coating of copper vitriol. The poles had to be driven down at least two meters into the ground in order to get below the ground frost. Otherwise the top of the poles could be moved as much as 20 centimeters as the poles were affected by the thawing of the frozen soil. The poles were at first planned to be placed in a zigzag pattern on both sides of the railway, but due to a local engineer that idea was dropped in favor of placing them alongside one side of the tracks. One main reason for that was the snow clearance made by a powerful rotating snow thrower mounted on a train. The snow was hurled with such a force that there was a sincere concern that this could damage the experimental line. However, the overhead contact system in Vassijaure was able to stand up to the tests and this showed that the harsh climate would not become a problem.

The idea of using wooden poles was later abandoned in favor of poles made of iron. Even if iron poles were more expensive and heavier they proved to be superior to those made of wood. Wooden poles had several disadvantages as they could burst into flames due to broken isolators, if they were not properly impregnated they could rot and break during storms, and the weight of the wires could bend them and cause disturbances. It seems that past experience using wooden poles for telegraph lines, together with the tests made in Stockholm and

Vassijaure, were the reason why the Bureau of electrical power decided to use iron instead of wood in the production of all the 2 700 poles used during the electrification.

Thorough tests of isolators were also made, initially by the Bureau of electrical power and later together with both Siemens and ASEA, in order to make sure they would be sufficient during heavy rain and snow. It had been shown that some earlier kinds of isolators used in southern Sweden could not cope with wet snow so well. They only managed to sustain 30 000 volts before flash-over. A stronger isolator had to be used and tests with water showers confirmed that the sturdier type managed up to 50 000 volts which was satisfactory as the overhead contact system was made for 15 000 volts. The tests also showed that regular isolators used on ordinary transmission lines could not be compared with isolators used at railways. This was because the latter were subject to pollution from both locomotives and tracks.

Knowledge gained from testing also determined what kind of material to use for wires. Tests carried out by the Bureau of electrical power at the test railways in Stockholm 1905-1907 had shown that wires made out of iron corroded if they were exposed to smoke from steam locomotives. Galvanization proved to be of some protection but the best way to protect iron wires was by painting them. However, painting wire was a very time consuming job and it had to be redone every year. Wires made of copper or bronze were better and it was decided that the wires used at the Frontier Railway should be made out of copper and made 8-shaped of 80 mm^2. A problem during wintertime was that snow gathered upon the wires and could weigh them down. This was solved by the ingenuity of the people working on the railway as they invented different ways to get rid of the snow and ice by throwing specially designed objects on the wire but still maintaining necessary safety precautions.

There were three tunnels and about 5 kilometers of roofed snow fences of wood to protect the railway from falling snow. Both the tunnels and snow fences had to be adjusted in order for the overhead contact system to work. The wire could not be placed too high or too low as it had to be in correlation to the pantograph on the locomotive. It was decided that the wire should be at least 4.7 meters above the tracks in tunnels and snow fences and 5.5 meters on the other parts. Many of the lower snow fences were either demolished or rebuilt in order to be in accordance to the new standard. Another problem in both tunnels and snow fences was running water that could gather in cavities and around the wire and freeze during winter months. This could be a serious problem and was partly solved in the tunnels by strengthening the vaults with concrete and in 1914 also by tar-boiling the isolators. The roofs of the snow fences were from 1914 and onwards isolated with asbestos cement sheeting or tar paper after many incidents with broken isolators were reported. Some isolators were fastened to near the wooden roof and if they broke they could set the fence on fire. The problem was above all the large amount of snow that gathered on top of them and melted during thaw. It was also too costly to shovel the snow away by hand so insulation of the roofs became a good alternative.

Even the construction of all the different buildings needed for the electrification had to take the harsh climate into consideration. The four transformer houses were, for instance, delayed one entire year because the necessary blue-prints were not ready in time for the winter. The problem was the excessive correspondence between the Bureau of electrical power, Siemens, and ASEA which slowed the building process. All blueprints had to be approved by the Bureau of electrical power before the local workforce could start the groundwork of the different buildings. A large number of alterations made by the Bureau of electrical power further delayed the work along the Frontier Railway. When the engineers in charge of the local workforce become aware of the fact that they could not have the walls and roof ready in time for winter the Board decided to stop and resume the work next spring. It was easier to cover and protect foundation walls against snow than to cover half-ready walls and roof beams from the ravaging winter storms. It was important to take winter conditions into consideration and all the buildings had to be built to withstand cold, snow, and storms irrespective of their function. The large workshop in Kiruna had to be equipped with a boiler to keep the heat and this was also the case for all offices, homes, and transformation stations as well.

Rolling stock

The usual steam locomotives used at the Frontier Railway hauled 28 freight wagons with iron ore and a small carriage. At the steepest slopes these trains had to be assisted by a pushing locomotive. However, the smoke from the locomotive in front was disturbing for the personnel on the back, especially in snow fences and the 1100 meters long Nuolja-tunnel. Another problem occurred during starting and stopping as the two locomotives had no means of communication between them. This sometimes resulted in the damaging of the couplers on wagons. They could be straightened out when the chain of wagons wrenched during start. The National Railways Board wanted to eliminate these problems and did not believe they would continue after the electrification. In order to increase the transportation capacity the Board planned that each electric locomotive would haul 40 loaded freight wagons; this was the largest amount of wagons that could meet at any station due to the length of the passing tracks. The electric train sets would also use a pulling and a pushing locomotive as it was believed that the total weight of 1 855 tons was too heavy for only one locomotive and that the couplers were too weak and would break. It would be too expensive to change the couplers on all the 1 800 freight wagons used to transport iron ore on the line.

Siemens and ASEA were supposed to build 13 electric freight locomotives and two passenger locomotives and had to deliver them fully operational until June 1 1914 according to the contract. Siemens was going to build eleven of the freight locomotives while ASEA built the rest. All locomotives had to be assembled in Sweden and only 35 percent of the material could be imported. A large number of blueprints were drawn during 1910-1912 at drawing-tables in Berlin, Västerås and Stockholm. All prints had to be inspected and approved by the Bureau of electrical power in Stockholm and prints were sent between the different offices for information and upgrading. However, the vast correspondence also contributed to uncertainties as many letters with information and plans were not sent to all parts at first and vital information could therefore be delayed for weeks. This irritated the Bureau of electrical power and especially its director, Ivan Öfverholm. The two firms had consequently to establish an office in Stockholm during 1912 to make the continued cooperation easier.

The many changes called for by the Bureau of electrical power made the work proceed very slowly and in December 1913 the delivery date was pushed forward. The first locomotives arrived in Kiruna in April 1914 and others soon followed. But the locomotives still suffered from different defects even though these were eventually solved. After the outbreak of the First World War in August 1914 some vital parts like carbon brushes became difficult to obtain, something which also affected the electrification. As soon as the first locomotives arrived in Kiruna tests with wagons were accomplished. The locomotives were built as twin locomotives, facing each direction. They were designed to be able to run at 50 km/h while the passenger locomotives could drive as fast as 100 km/h, considerably faster than the steam locomotives previously used. However, the tests showed that couplers were still damaged and sometimes broke during start and soon experiments began to solve this problem. Three different kinds of train sets were used in the trials; two hauling locomotives at the beginning of the train, one pulling and one pushing, and one hauling and then another one following after ten wagons. Tests were also carried out with 28 wagons instead of 40.

The locomotives were also equipped with a number of details to simplify its operations in snowy and cold weather. Windscreen wipers were mounted to keep the windscreen free from rain and snow and increase visibility. Sand boxes were placed in front of the driving wheels and could be used to sand the tracks when they were slippery from ice, oil, or water. A snow plough was mounted in the front. Every locomotive was equipped with heating in the driver's cab and a small stove where the driver could heat his food or coffee.

Illustration nr 6 (An O-locomotive hauling wagons filled with iron ore on the Frontier Railway, www.historiskt.nu)

The electrified Frontier Railway was formally opened in January 1915 but many of the delivered locomotives still had many faults and it took almost two more years until most of these were solved. Still, the electrification turned out to function very well and the parliament later decided to electrify the rest of the Iron Ore Line to the coastal town of Luleå. The upgrading was completed in 1923 and during that same year the Norwegian part of the Iron Ore Line, the Ofotenbanan Railway, connecting Riksgränsen and Narvik was also electrified. The success of the electrification of the Frontier Railway became the starting point for Sweden´s massive railroad electrification during the following decades.

Discussion

They were indeed bold, the investors[27] and engineers involved in the establishment of the water- and wastewater system of Luleå town as well as those involved in the electrification of the Frontier Railway. These undertakings represented extremely large investments under very insecure conditions. Never before had such infrastructural systems been established under such extreme weather conditions, and when it came to the water- and wastewater system in Luleå, never before had the city made such a big investment and with such little local expertise. This is probably the most important lessons from the two historical infrastructural investments in focus for this study, for the production of both more sustainable systems and for systems for cold climate. Such boldness ought not the least to be inspiring to those

[27] The management of Luleå town and the national parliament.

involved in the contemporary sustainability debate, policy design and implementation, where related investments in infrastructural change often ought to be as bold in order to overcome the systems' sluggishness to change and to achieve the desired results. The radical and large-scale investments made under great uncertainty, illustrated by the cases, are not entirely different from some of the measures needed to address the climate change challenge. An important component of the uncertainties in the investments discussed in this paper can further be derived from the harsh climate of the region within which they took place; this was probably most prominent in the case of the electrification of the Frontier Railway.

By studying and comparing technical change at the micro-level in connection to the establishment of the Luleå town water- and wastewater system and the electrification of the Frontier Railway at the beginning of the 20th century, we have found three general lessons of relevance to the process of infrastructural change. These have to do with: 1) uncertainty and the need of boldness; 2) context-dependency, and; 3) the critical importance of experts. The local establishment processes were marked by uncertainties and the related technology choices were based on gradual, sequential decisions made at the micro-level with a strong connection to the local and scientific context, and with an often floating distinction between technology choices on the one hand and technical development on the other.

In case of the electrification of the Frontier Railway, a number of uncertainties had to be managed, i.e., technology choices had to be made regarding the electric power system and the rolling stock as well as of snow fences, buildings etc. A number of uncertainties were in turn related to the harsh climate, not the least to the snow loads to be managed during winter. Technology was developed (rather than chosen) through interplay between trial and error activity at the very micro-level and drawing boards in Stockholm, Berlin and Västerås, where the importance of the trial and error activities indeed should not be underestimated. The rather large number of possessors (e.g., engineers at the Bureau of electrical power, Siemens, and ASEA) of central knowledge to the establishment process, in turn led to a great deal of correspondence as means of communication, added uncertainties and tended to slow down the establishment process in comparison to the case of the Luleå water- and wastewater system where the city council of Luleå, in contrast to the Bureau of electrical power, had to put almost all their trust to the knowledge of consultants.

For the city council of Luleå it was of course associated with much uncertainty to be this dependent on consultants, and it became important to choose the right consultant. The specialisation of engineer Hansen, i.e., subsoil water, turned out after some time to be incompatible to the local requirements. However, once engineer Richert and his technology of specialisation, the newly developed artificial infiltration technology, was chosen and the construction process started it ran fairly smoothly, i.e., a complete water- and wastewater system was established within two years after the decision was taken in the city council to launch the project. The fact is that the town of Luleå, through engineer Richert, was able to benefit from the most novel scientific and technical findings implemented in its water- and wastewater system (the same water supply is still used today). He thus functioned as a direct contact between the scientific world and the technology choices made at micro-level. The local establishment process of the Luleå water- and wastewater system is all in all characterized by a close connection between science and technology; parallel intensive development phases within disease science, hydrology and chemistry, as well as within the technologies of drilling and water-hauling, are all clearly mirrored in the process.

This paper has attempted to shed historical light on infrastructural change at the micro-level and has found support for the often floating distinction between technology choice and development when technical and scientific knowledge gets connected to a local environment, such as to local geographical prerequisites. Moreover, we have seen scientific knowledge opening up technical alternatives at the micro-level as well as imposing constraints on what is technically possible, and have illustrated the crucial importance of the consultants for the processes of establishment and technology choice.

We can assume the technology choices at the micro-level of contemporary infrastructural change related to cold climate and to extensive investments in strive for ecological and social sustainability, to be equally context-dependent as in the historical cases in focus of this paper. There is however reason to believe that it would not be as probable with the same role of the experts, such as in the case of the Luleå water- and wastewater system-establishment with the prevalent direct contacts between science and the technology choices. The more limited direct scientific influence can be understood by the growth in social superstructures of the infrastructural systems over the 20th century, i.e., in related organisations – such as local/regional expertise – institutions and users, alongside with a general democratising and politicising process of society. These superstructures have generally and inevitably made processes of infrastructural change both more social in character and difficult to change, e.g., with the advent of new scientific findings. This has been observed in the literature, which shows that the establishment of more sustainable infrastructural systems requires a transformation of both material and social arrangements. The above makes it motivated to continue doing empirical studies of infrastructural change in the past, but to a greater extent include social changes in the analysis. This should be accomplished by focusing on changes at the micro-level of since long-established infrastructures, such as during the expansion of an infrastructure in a local context, or during an additional radical invention within a mature system.

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