Janne M. Korhonen Constructed solutions to constructed constraints

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Department of Management Studies

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Resource scarcities and technological change

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Janne M. Korhonen

Aalto University
School of Business
Department of Management Studies

Main dissertation advisor
Professor Liisa Välikangas, Aalto University, Finland

Preliminary examiners
Professor Joseph Lampel, University of Manchester, United Kingdom
Professor Timo Myllyntaus, University of Turku, Finland

Opponent
Professor Joseph Lampel, University of Manchester, United Kingdom

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Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

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Janne M. Korhonen

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Abstract

Is necessity the mother of innovation, and if so, why many extremely urgent problems such as climate change or cheap electricity storage still remain unsolved? Why even extraordinary incentives often fail to generate technological change that would solve the problem in hand?
This thesis examines the relationship between resource scarcities, in particular energy and raw materials, and technological change. Drawing on and developing the literature on resource scarcities, constraints and innovation, the study presented here helps us to understand how perceptions of scarcities influences technological change, and how scarcities may even reproduce themselves through technological decisions influenced by such perceptions. Scarcities are found to be very much a question of power between those who would use the resources and those who control the resource use. Amartya Sen's concept of "entitlement" or its developments (e.g. Daoud's "quasi-scarcity") are found to be necessary for understanding how technology developers - technologists - actually respond to constraints and scarcities. In short, the technological responses to resource scarcities, such as the development of less resource intensive technologies, are heavily determined by how much power the technologists possess relative to resource controllers. This power, or entitlement to a resource, depends not only on the importance of the industry or the resource, but also on the perceptions of technology. In cases where scarcity-altering novel innovations are perceived to be within relatively easy reach, the technologists have less power and lower entitlement to the scarce resource.
These findings are based on and illustrated by two case studies in history of technology. The main case study examines the history behind one mining company's decision to develop a radically novel "flash smelting" copper furnace as a response to post-Second World War electricity shortage in Finland. This development, by state-owned copper producer Outokumpu, slashed energy requirements for copper smelting, and became almost the standard method for copper smelting, one point producing as much as 60 percent of world's primary copper. The second case study looks at the development of jet engine cooling systems in the Second World War Germany as a result of Germany's lack of access to nickel, a strategic metal necessary for, among many other uses, high-temperature jet turbine components.
As such, this thesis contributes not only to the emerging "ingenuity" and "scarcity, abundance and sufficiency" research streams, but also to the history of technology and to the history of post-war Finland, particularly the so-called "war reparations period" (1944-1952).

Keywords Scarcities, Constraints, Technological change, Copper smelting, Finland

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Tiivistelmä

Tekijä
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Tiivistelmä

Onko pakko keksintöjen äiti, ja jos on, miksi emme ole keksineet ratkaisuja moniin äärimmäisen pakottaviin ongelmiin, kuten ilmastonmuutokseen tai sähkön edulliseen varastointiin? Miksi jopa erittäin hyvät kannustimet eivät useinkaan johda ongelmat ratkaisevaan teknologiseen muutokseen?

Tämä väitöskirja selvittää resurssiniukkuuksien, eritoten energian ja raaka-aineita koskevien, yhteyttä teknologiseen muutokseen. Väitöskirja pohjautuu ja kehittää tutkimuskirjallisuutta resurssiniukkuuksista ja -rajoitteista sekä innovaatiosta. Tutkimus auttaa ymmärtämään kuinka mielikuvat niukkuuksista vaikuttavat teknologiseen muutokseen, ja miten niukkuudet voivat jopa toisintaa itseään mielikuvien ohjaamien teknologisten päätösten kautta. Niukkuuksien todetaan olevan hyvin pitkälti valtakysymyksiä niukkoja resursseja käyttämään pyrkivien ja resursseja kontrolloivien välillä. Niukkuuksien vaikutusta teknologioita kehittävien "teknologistien" ratkaisuihin ei voi ymmärtää ilman Amartya Senin oikeutus-käsitettä ("entitlement") tai siitä johdettuja konsepteja, kuten Daoudin "kvasiniukkuuksia". Lyhyesti, teknologiset vastaukset niukkuuksiin, kuten vähemmän resurssi-intensiivisten teknologioiden kehittäminen, riippuu suurelta osin siitä, miten paljon valtaa teknologisteilla on suhteessa resurssien jaosta päättäviin. Tämä valta, tai oikeutus resurssiin, ei riipu yksin teollisuudenalan tai resurssin tärkeydestä, vaan myös teknologiaan liitetyistä mielikuvista. Silloin kun niukkuustilaa muuttavien uusien innovaatioiden arvellaan olevan suhteellisen helposti kehitettävissä, teknologisteilla on vähemmän valtaa ja alhaisempi oikeutus niukkaan resurssiin.

Tutkimuksen löydökset perustuvat ja niitä havainnollistetaan kahdella teknologian historiaa selvittävällä tapaustutkimuksella. Pääasiallinen tapaustutkimus käy läpi suomalaisen valtio-omisteisen kaivosyhtiö Outokummun päätöstä kehittää radikaalisti uudenlainen "liekkiuuni" kuparinsulatukseen vastauksena sodanjälkeisessä Suomessa vallinneeseen sähköpulaan. Kyseinen teknologia vähensi selvästi kuparinsulatuksen energiavaatimuksia, ja siitä tuli liki standardimetodi kuparinsulatuksessa: eräässä vaiheessa jopa 60 prosenttia maailman primäärikuparin tuotannosta tehtiin Outokummun toimittamilla uuneilla. Toinen tapaustutkimus tutkii suihkumoottoreiden jäähdytysjärjestelmän kehitystä toisen maailmansodan aikaisessa Saksassa vastauksena Saksassa vallinneeseen nikkelipulaan: nikkeli oli strateginen metalli, jota tarvittiin monien muiden käyttökohteiden ohella suihkuturbiinien vaatimien kuumalujien metalliseosten raaka-aineeksi. Väitöskirja edistääkin paitsi nousevaa "nokkeluus"-kirjallisuutta ("ingenuity") ja niukkuuksien, runsauksien ja riittävyyden ("scarcity, abundance and sufficiency," SAS) tutkimusta, myös tekniikan ja sodanjälkeisen Suomen sekä sotakorvauksien historiaa.

Avainsanat Niukkuudet, rajoitteet, teknologinen muutos, kuparinsulatus, Suomi

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In a project of this scale and length, acknowledging the help of everyone who contributed — knowingly or not — to the completion of the work is impossible, solely because memory fails and the author will not himself be aware of all the influences other people have had on him. For this reason, the first persons I'd like to thank are those I've forgotten: I'm sorry!

Of the contributors who I can remember, my then-colleagues at Seos Design, Antti Pitkänen, Pekka Kumpula and Teemu Vaarakallio, deserve to be mentioned first. The entire research question motivating this thesis grew from my experiences with you, and this thesis would not have been even started without your tacit approval to work on the research plan during quiet hours at the office; I hope the business did not suffer unduly. Second, Liisa Välikangas, my supervisor, deserves credit for believing in my research idea, rudimentary as it was, and for guiding, supporting and encouraging me even as the research dragged on and I was distracted by other projects. Besides seeing this project through, her patience is probably the single most important reason why I was able to write not just this thesis but also two non-fiction books, and she should claim at least some credit for the creation of a new, rapidly growing environmental organization, the Finnish Ecomodernist Society, whether she agrees with them or not.

My experiences with other people at the Helsinki School of Economics and Aalto University have also been nothing less than pleasant. Without Armi Temmes, I would probably be still hunting for a case study; by having the insight of loaning me an obscure book about the history of Outokumpu's flash smelting, she made this work possible in the first place. I'm also fortunate in that Marjatta Vuorinen retired only after my manuscript was already complete. Looking back, I feel sorry for those current PhD students who have to do without her support and ability to provide quick answers to our stupid questions about the workings of the school bureaucracy. Her help in such practical matters was a major load off our backs, as I believe others would agree.

Other people who rarely receive as much credit and thanks as they should include all the staff at the university, who work hard to maintain the infrastructures of learning and study. A special mention needs to be made for the librarians, who speedily delivered even the most esoteric materials I could think I might need, up to and including a bedsheet-sized copy of wartime German jet engine drawings. Likewise, the staff at the Central Archives for Finnish Business Records (ELKA) were most helpful for my quest to comb through the Outokumpu archives held there.

Research could not proceed without discussions with other researchers, both in informal settings and in the scholarly discourse conducted through journals and conferences. Of the former, the most important to me have been semi-regular chats with other PhD students from the Department of Management, particularly Eeva-Lotta Apajalahti, Rebecca W. B. Lund, Maarit Laihonen, Ines Peixoto, Tatu Lyytinen, Jouni Juntunen and Jukka Rintamäki. I still don't quite understand what you were working on, but I've long since learned that the salt mines can be much more enjoyable if one's not toiling alone.

For more specific feedback, I thank all the anonymous reviewers who, over the years, have tried to correct my mistakes. Particular thanks are due to the two pre-examiners, Joseph Lampel and Timo Myllyntaus. Your comments are much appreciated and will be heeded in the future, not just in articles based on this thesis but in other research I hope to conduct. That the thesis is not as good as your input could make it is my fault alone.

Equally important for the work has been the material support provided by several Finnish foundations. The Foundation for Economic Education provided the grant that started this whole process, as well as other support later on. I was extremely fortunate in that the Jenny and Antti Wihuri Foundation provided me funding for three full years, enabling me to pursue not just this thesis but also other projects — such as two well-received non-fiction books about energy — that I believe do contribute to the foundation's stated mission of promoting Finnish cultural and economic development. Such academic freedom as I've enjoyed is rare these days, and wish to extend my most sincere thanks to the trustees for trusting in me. Last but not least, the HSE Foundation contributed in a time of need, for which I'm deeply grateful.

The entire process towards the doctorate has been a learning experience, in which this thesis is in some ways almost an incidental byproduct. I've learned many valuable things about the world, myself, and other people in the process that has seen me re-examine not only the history of Outokumpu but even my political views and the purpose of life. Many people, including all those already mentioned here and countless others, have taught me something along the way. However, no one has taught me more nor more important things than my dear wife and best friend, Tanja. She is not only the smartest and the best thing that has ever happened to me, but she has also provided some of the most insightful comments about my research that I've received from anywhere. She is also the one person without whom I almost certainly wouldn't have been able to complete this project. Therefore, I dedicate this thesis to her, with my love.

In Turku, 18.11.2017

Janne M. Korhonen

Chapter 1

Introduction

1.1 A tale of two technologies

“The age of electricity and of copper will be short,” prophesied a speaker before no doubt surprised members of the Commonwealth Club of California in the summer of 1924 (Joralemon, 1924). No matter that the age of electricity seemed to be only starting: According to the bleak picture the speaker painted, the rapid spread of electrification contained the seeds of its own downfall. Electrification would result to ravenous demand for copper, while known deposits of this valuable metal were being exhausted. “At the intense rate of production that must come, the copper supply of the world will last hardly a score of years.”

“Our civilization based on electrical power will dwindle and die,” was the gloomy conclusion. The doom sayer, Ira B. Joralemon, was no crank: since graduating from Harvard University with bachelor’s and master’s degrees in mining and metallurgy in 1907, he had worked as mining engineer, geologist and manager at various copper mines in the United States, Siberia and South America, and played a key part in the development of the first large open-pit copper mine in Arizona. In 1922, he had set up his own consultancy which would keep him busy for the next fifty years and earn him a place in the hall of fame of American mining (Anonymous, 2016). This was an established and respected expert on his own field, and his tidings were grim.

What ordinary members of the Commonwealth Club might have thought of the address is not recorded, but geologists and mining engineers expressed their doubts (Joralemon, 1924). Few weeks after the speech, an editorial (Anonymous, 1924) to *Engineering and Mining Journal,* perhaps the leading professional publication in the field, summarized the objections: Metallurgical methods will advance, and prices will rise as copper becomes more scarce. In combination, this will make poorer deposits and deeper mines profitable, and balance will be restored as the iron law of supply and demand does its thing. New deposits will be found (again, as rising prices stimulate prospecting), and technological advance may mean that electrical industry might do just fine without: “Maybe copper won’t be required at all for transmission purposes; we may just use the ether.” (Anonymous, 1924, p. 122)

While wireless transmission of electricity through the “ether” is still under development, the other mechanisms worked more or less as the *Engineering* *and Mining Journal* confidently predicted. By 1924, world copper production had recovered from its post-war slump to about 1.4 million metric tons per year (Julihn and Meyer, 1933). Despite Joralemon's warnings, by 2014 annual copper production had risen to around 18.5 million tons (USGS, 2016). All the demands that Joralemon feared would materialize and more, materialized - and were met with ease. Mining and metallurgical technologies had advanced in leaps and bounds, and whenever copper seemed to be in short supply, price increases motivated producers to invest in better technologies and prospectors to head out in the remaining unexplored corners of the globe.

Joralemon had been too pessimistic by far, but even as he spoke, another, once promising industry was dying. By 1920, almost all the electric car manufacturers in the world had either gone out of business or switched to gasoline-powered cars (Westbrook, 2001; Kirsch, 2000). Only twenty years earlier, the automobile market had been divided almost equally between gasoline, steam, and electric vehicles. In 1900, 1684 steam-driven, 1575 electric, and just 963 gasoline-engined cars were manufactured in the United States (Westbrook, 2001). Just a year earlier, an electric vehicle had captured the world speed record, and proclamations that electric car was *the* future were not hard to find (Kirsch, 2000). From 1900 to about 1912 could be considered to have been a "golden age" for electric vehicles: In 1903, London counted more electric than gasoline vehicles (Westbrook, 2001), and electric cab and bus companies were developing rapidly, particularly in the United States (Kirsch, 2000).

However, at the same time gasoline engines — those noisy, unreliable and awkward contraptions that required both strength and expertise to use — were developing rapidly. They were still awkward compared to electric car's silence and ease of use, but they were much cheaper. In 1909, when the iconic Ford Model T was introduced, it was already clear that the race had been won by the internal combustion engine (Westbrook, 2001). In 1912, a record 30 000 electric cars were in use in the United States; but there were also 900 000 gasoline cars. In 1921, the last American new-model electric car of the era offered a range of 60 miles for a price of $1200. A Model T sold for $300. (Westbrook, 2001)

The reasons for the ascendancy of gasoline over electricity are complex (for a thorough overview, see Kirsch, 2000), but undeniably, one of the major reasons was the battery. Simply put, battery could not begin to compete with gasoline in energy density or simplicity. As a result, electric cars had to cope with heavy and above all expensive batteries, while their range was sadly limited. While battery alone probably did not doom electric vehicles for nearly a century, it is clear that had a substantially better and cheaper battery been developed, the race would have been far more even. The significance of battery improvements was well understood at the time, and for a time, proponents of electric cars remained hopeful. In 1897, the periodical *Electrical World* devoted for the first time ever an editorial to "horseless carriage;" in it, the magazine proclaimed that "[t]here is not the least reason [...] to assume that the [battery] will not undergo great and marked changes and improvements. In general, whenever there is a demand for a specific improvement or invention, it soon makes its appearance [...]" (Anonymous, 1897, p. 468).

Almost identical statements of the great need for a better battery were repeated in the following years (Anonymous, 1899, 1900, 1901).[1] Invariably, these

[1] I'm indebted here to David A. Kirsch, who has collected the original material for his book

arguments expressed faith in the demand-pull theory of innovation: If the need is sufficiently great, an innovation will appear. The explosive growth of automobile industry proved that a need existed; furthermore, better, cheaper batteries would be a boon not just for electric cars but also for the entire electricity sector.

For a moment, it seemed that the call had been answered, as acclaimed inventor Thomas A. Edison announced his intention to solve the battery problem once and for all (Kirsch, 2000). However, even Edison's genius was able to produce only a modest improvement in form of novel nickel-iron battery he introduced in 1901. Unfortunately, this battery was even more expensive than the lead-acid batteries commonly used, and manufacturing difficulties compounded the problem (Kirsch, 2000; Westbrook, 2001). While batteries continued to improve incrementally, the desired leap of innovation did not occur. No matter how huge profits its inventor would be able to reap, a better battery was not to be, and electric cars lost their opportunity to shape personal mobility to perhaps something very different from how we experience it today.

1.2 Motivation: Is necessity really the mother of invention?

From whence the difference between these cases? If, as common wisdom says, necessity is the mother of invention, why did necessity bring about great advances in copper production, but only minor improvements in batteries?[2] Can we learn something from the technological response to past necessities, and perhaps understand better when to take seriously the Joralemons of today, or dismiss the sooth-sayers of unbridled innovation and the law of supply and demand?

In other words, should we, or should we not, expect that increasing scarcities beget innovation *that allows us all to be at least as well off as before the scarcities?* When we should and when we shouldn't? And if we can't expect to be as well off, can we at least expect that our well-being isn't decreased unduly? When are scarcities or constraints too stringent for us to expect a happy outcome? What constitutes a "too strict" constraint anyway? And what, actually, are constraints? These questions summarize the motivation behind the study you are currently reading. Since they were only poorly developed in existing literature, they also became topics of this investigation.

I was originally motivated to study this subject as a result of my experiences at Seos Design, a Finnish design company working to promote sustainable product development practices. Between 2007 and 2010, I was involved in several projects where an additional goal of the design project was the reduction of environmental footprint of a product. In practice, this meant sometimes severe constraints on e.g. material choices, assembly practices or energy use. Curiously and somewhat contrary to our expectations, we concluded that our results were often (although certainly not always) better than what we'd have produced without the "extra" constraints we had more or less voluntarily imposed on the

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The Electric Vehicle and the Burden of History (2000).

[2] At superficial level, one might be tempted to explain the difference simplistically, for example, by arguing that copper is a commodity whereas batteries are complex technological artifacts. However, one could also argue that electricity stored in batteries is a commodity too, and wresting poorer and poorer ores from the ground required in some cases extremely complex technological artifacts.

design. For example, after focusing on the environmental impacts of exposition stands, a design developed by our managing director was able to reduce material use for a stand by as much as 97 percent, while simultaneously reducing costs by a third and providing benefits that were simply unattainable through traditional stand design practices.

Such experiences ran contrary to the model of creativity that had been implied in my previous education and experience. This model suggested that creativity requires "creative freedom" and that constraints to that freedom are detrimental to the quality of work produced. Clearly, this was not always the case; and equally clearly, *some* constraints to creative freedom had beneficial effects. This is no new knowledge: as veteran designers told me, one of the very few universal axioms within design industry is "creativity requires constraints." Similar sentiments have been uncovered by creativity researchers (e.g. Rosso, 2014; Hargadon and Sutton, 1996; Stokes, 2006), who also corroborated my intuition: creative teams are known to actively place constraints on themselves as a way of structuring or bounding their work in order to enhance creativity. Constraints provide a starting point and the basic foundation for design to evolve. Without constraints of some sort to guide their work, even the best designers will be lost in a sea of boundless possibility.

On the other hand, it is also clear that too severe constraints will stifle creativity and may result to substandard "mend and make do" designs, or even to a failure to find any feasible solutions at all. In trivial, economic sense, this is not a problem since as long as some form of economic system remains, *some* kind of substitute will always be found to any scarce resource. Even lack of any feasible solution can be considered to solve the problem of constraints: in economics, the assumption is that if scarcity of some resource causes some previously possible activity to become impossible, it must happen because some substitute, alternative consumption bundle begins to offer a more attractive trade-off for scarce resources.[3] In real-word terminology, if oil becomes scarce but good alternatives to gasoline cannot be found, we are still assumed to be quite well off since we simply shift our habits and preferences accordingly. We might be forced to use soot-spewing wood gas engines and other imperfect substitutes and accept greatly limited mobility, but in economic sense, the scarce resource is now substituted and the "problem" is solved.

However, while such trivial and tautological "solutions" may be acceptable in theory, in real life we are still concerned about the potential loss of well-being as a result of scarcities and imperfect substitution. To those old enough to remember wartime rationing, the "ersatz" substitute goods produced from scarce resources still evoke recollections of disdain. Therefore, the real question is not whether any and all resources can be substituted — as long as some economic system survives, the answer is yes, provided one is not too fuzzy about the question "with what" — but whether scarcities and constraints, as a rule, result to technological change that at the very least does not make us all less well off. Preferably, of course, technological change should make us *better off* than before.

The question can be rephrased using a definition for "ingenious" innovation offered by Lampel and others in their review of the emerging ingenuity research

[3] For example, a poor harvest does not make beer brewing "impossible" in the strict sense; it simply makes this use of scarce grain less attractive than using it all for bread.

stream in organizational literature (Lampel et al., 2014). According to this definition, ingenuity is displayed when someone develops, usually as a response of some hardship or scarcity, a solution that is significantly *better* than what was expected. In other words, the key question of this thesis is as follows: *what can we say about the probability that constraints and scarcities lead to ingenious innovations?*[4]

While the primary interest of this thesis is obviously academic, the question motivating this thesis carries much broader implications. We live in a world where necessities are abundant. In developed countries, many want more for the sake of more; for others, critical resources such as clean water and abundant energy are still scarce. Globally, one of the increasingly scarce "resources" is the ability of biosphere to act as a sink for wastes of our economic activity — particularly of carbon dioxide. As the world population is heading towards nine to eleven billion around the mid-century, it is to be expected that even some previously abundant resources may become scarce and cause new, pressing necessities. At the time of writing, growing concern has been raised about the availability of rare earth metals, which see widespread use in modern electronics and electric infrastructure (Veronese, 2015; European Commission, 2014; Tuohinen, 2016). Many other works have warned about possible, or even impeding, scarcities of easily accessible oil and other fossil fuels (e.g. Heinberg, 2003; Greer, 2008; Partanen et al., 2014) and mineral resources (e.g. Kunstler, 2006; Bardi, 2014), water scarcities are increasingly a fact of life in many areas around the world (Wolfe and Brooks, 2003; Anand, 2007; Oberkircher, 2011) and even sand is believed by some to become a scarce resource in near future (Gillis, 2014).

For quite some time, academics, pundits, activists and politicians have wondered and debated what effects — if any — resource crises may ultimately have on individuals, organizations, and the human civilization. The debate has raged at least since the publication of Thomas Malthus's *An Essay on the Principle of Population* (1798), and shows no signs of abating any time soon. In one corner are those who argue that resource scarcities of one sort or another will ultimately pose serious problems to humans and possibly doom the human civilization; in another, those of more optimistic bent claim that due to human ingenuity, scarcities pose no threat nor bounds to human prosperity. Furthermore, a third position maintains that resource scarcities are not the real problem, but the maldistribution of both resources and wealth is. For a while in the 1970s and early 1980s, the publication of influential Malthusian-inspired works such as Ehrlich's "Population Bomb," (Ehrlich, 1968) and Club of Rome report "Limits to Growth" (Meadows et al., 1972), combined with the shock of 1973 oil crisis and the rise of the environmental movement, brought the scarcity topics to the forefront and drew the battle lines described above. However, the uncertain nature of evidence, sometimes justified accusations of techno-pessimism, and, probably most importantly, the failure of scarcity-induced crises to materialize in the time frame prophesied by some important neo-Malthusians did much to undo this important discussion. According to a noted scholar of scarcity Thomas Homer-Dixon, who classified the above debating positions as neo-Malthusians, neoclassical economists and distributionists respectively (Homer-Dixon, 1995),

[4] In economic terms, ingenious innovation might be also defined as an innovation that expands the production-possibility frontier.

by the 1990s the debate had already "become sterile" and exchanges between optimists and pessimists achieve little. A sign, perhaps, that at stake on both sides is not just a question of scientific and political importance, but deeply held values and identities?

Nevertheless, another observation made by Homer-Dixon and others more than twenty years ago is still valid. The paradigms underpinning these positions have had, and continue to have, great influence. Generally speaking, neo-classical (that is, mainstream) economists and those influenced by mainstream economic thought tend to refer the issue to the iron law of supply and demand: as long as economic institutions, notably markets, perform properly, they will provide sufficient incentives to encourage proper conservation of scarce resources and their substitution through technological innovation. As a result, provided that said institutions do in fact function properly, the question of resource scarcities becomes a moot point: necessity will always mother inventions, of one sort or another. Inventions and incentives will thus elegantly solve whatever problems our societies might face. If a resource becomes scarce, its price will rise. This rise in prices causes people to re-evaluate their habits and obtain equivalent utility from alternative sources - and provides some with an opportunity for gain if they can provide these alternatives. Even if some resource becomes simply impossible to obtain, in aggregate no great harm will be done.

Quite the opposite: scarcity and necessity are argued to be the causes of not just innovation but economic development and growth in general. According to no less an authority than Adam Smith, the necessity of obtaining otherwise scarce resources by trading with others is at the root of specialization of labor (Friedman, 2005, p. 48). Since no individual person can produce everything she wants or needs, there is an incentive to specialize and trade with others. In his treatise on economic growth and its effects on political and social history, Friedman (2005) argues that in the theories of early economic thinkers, scarcity of resources — a condition that tends to generate necessities — is the driving force behind all economic progress. Similar arguments have been put forward by some proponents of environmental regulation, most notably by famous economist Michael Porter, whose "Porter hypothesis" posits that strict environmental regulation can induce efficiency and encourage innovations that, overall, help commercial competitiveness (Wagner, 2003; Ambec et al., 2011; Porter and van der Linde, 1995a). According to this thinking, therefore, constraints and scarcities can result to the expansion of production-possibility frontier, or at least do not cause any great reduction of it.

Perhaps partly as a result of pervasive influence of mainstream economic thought, and partly due to the sterile nature of debates mentioned by Homer-Dixon, in these days popular discussions of potential resource scarcities in most developed countries are generally nipped at the bud even before they can really begin. After all, if economic theory predicts that all resources, once sufficiently scarce, not only can but *will* be substituted with the silent assumption that substitution does not inordinately affect our wellbeing and can even spur innovation that actually advances it, there is little reason to be concerned. Curiously, in ordinary conversation this logic is often allied with a market fundamentalist logic that tends to see anything that potentially imposes costs or limits on business as a bad thing in itself (see Rich, 2016).

Given such contradictions and the potential importance of the topic, as well as the ideological stakes involved, it is perhaps no surprise that mainstream economic theory has been repeatedly challenged, even though the challenges are currently largely confined to academic debates. While the orthodoxy remains strong in economics, a vigorous and growing, although not unified movement has begun to examine the problems of scarcities and constraints in more detail. On the level of economies, heterodox economists, particularly from environmental economics tradition, have for long argued that the classical economic concept of scarcity may fail to capture important details about the phenomena (e.g. Baumgärtner et al., 2006; Tchipev, 2006; Raiklin and Uyar, 1996). These researchers call for a more nuanced approach to economics that acknowledges the fundamental thermodynamical limits of our natural world: perfect substitutes do not exist, and while some resources may be possible to substitute in principle, they may prove to be inordinately difficult to substitute in practice. In terms of production-possibility frontier, many heterodox economists fear that scarcities do not lead to neutral, much less positive technological change, but instead are likely to cause a contraction in our material wellbeing. Many of these researchers draw from a resource economic tradition dating to the debates of the 1970s, while others, such as Daoud (2007; 2011), Lähde (Lähde, 2013) and other authors in "scarcity, abundance and sufficiency" field, approach the problem with a more general socioeconomic or even philosophical perspectives.

Since the task of actually developing substitutes for scarce resources generally falls upon companies and other organizations that largely make up the economy, it is noteworthy that a new breed of organizational scholars is simultaneously questioning the accepted wisdoms of resource-based views of the firm and now ask whether resource constraints can actually be a source of strength for the organization (Paeleman and Vanacker, 2015). Innovation management research in particular has shown interest in determining whether necessity is indeed the mother of innovation (e.g. Gibbert and Välikangas, 2004; Gibbert et al., 2007; Keupp and Gassmann, 2013; Weiss et al., 2011, 2014), and the rise of related topics such as "frugal innovation" and "bricolage" attest to the widespread interest within research community for "less is more" thinking. In organization science, research relating to questions of scarcity, constraints and innovation is slowly coalescing under the rubric of "ingenuity" studies (Lampel et al., 2011, 2014; Honig et al., 2014). While this research stream is still in its formative stages, a widespread interest in the topic has been apparent in the popularity of no less than four special issues devoted to the broad topic in four different journals since year 2000.[5]

Finally, there is also considerable research interest in how individual creativity is affected by various constraints (e.g. Moreau and Dahl, 2005; Stokes, 2007; Goldenberg et al., 2001; Finke et al., 1995). As organizations are ultimately groups of individuals and it is individuals who are ultimately tasked with innovating the solutions, this means that an emerging research platform of constraints, creativity, innovation and scarcities covers all important levels of analysis. There is, of course, sometimes considerable overlap between economics, organization studies, and creativity research, and lines between different disciplines are blurry at best. This overlap and multidisciplinary nature of ingenuity studies are only to be expected, since the questions motivating these studies are large and impossible to tackle using tightly focused theoretical approaches.

[5]Namely, *Long Range Planning* (6/2004), *Journal of Product Innovation Management* (2/2014), *Organization Studies* (4/2014), and *Creativity and Innovation Management* (2/2015).

From this brief overview, which shall be further expanded upon in the literature review in chapter 2, it is already clear that the topic of resource scarcities and their impacts on individuals, organizations and societies has been slowly but surely gathering steam over the last few years. The early debates have faded from public memory and the acute environmental predicaments — climate change foremost among them — are causing more and more people to question whether our current economic world-explanation is wholly adequate for the challenges of the 21st century. The stakes of this great rethink are vast beyond imagination: quite conceivably, a wrong answer could mean disastrous results to our common environment, our societies and perhaps the whole human civilization. Simultaneously, powerful interest groups are all too happy to uphold the status quo, as stronger responses to potential scarcities would almost certainly mean increased regulation and reduce profit margins for many established industries. Into this breach must public research wade, and I hope that this thesis could in some small way help us all to either avoid the coming thickets or at least better navigate them.

1.3 The focus and scope of this thesis

While the question motivating the study can be defined fairly simply — *what can we say about the probability that constraints and scarcities lead to ingenious innovations?* — the breadth of the topic requires one to be fairly selective in setting the scope for an investigation. From the start, it was clear that this study was going to study organizations coping with resource constraints. This is not only due to my academic home, the Organization and Management unit of Aalto University's School of Business, but also because it is organizations that will be ultimately responsible for developing (or failing to develop) the ingenious technologies. Therefore, understanding better how individual organizations have coped with constraints and scarcities may shed light on what we can expect from the economy as whole.

As the literature review in the following chapter shall show, other researchers have done a commendable job in exploring the question of constraints, scarcities and innovation from various viewpoints and using different methodologies. However, multiple authors have noted that most existing studies are more or less cross-sectional in nature, and lament a research gap in the paucity of longitudinal, comparative case studies of scarcity- or constraint-inspired or influenced technological change (Rosso, 2014; Lampel et al., 2014). Furthermore, even those longitudinal studies that exist (e.g. Dolmans et al., 2014; Rosso, 2014; Gibbert and Scranton, 2009; Yarime, 2007) tend to follow their research cases only for some years at best. While technological change sometimes happens quickly, it is rare that the full impacts of technological change will be apparent to research with such short time spans. In addition, obtaining data from ongoing and therefore sensitive innovations and innovation processes may be difficult.

These considerations led me towards the choice of historical method. Proper appreciation of technology's impact requires taking a long enough view at the history of some specific innovation and the industry around it. In many cases, decades of development may be necessary before the requisite perspective can form. Likewise, I shall try to show here that studying the "prehistory" of innovations is a fruitful exercise that may help explain some otherwise puzzling details of particular innovations. Furthermore, by examining historical innovations I would be able to avoid the problem of sensitive data, as technical details, archival sources and other accounts would be more easily available.

The decisive factor, however, was a fortuitous discovery of an innovation that seemed to suit my needs perfectly. While searching for suitable research cases, I chanced upon an account of the development of so-called copper flash furnace by Outokumpu, a Finnish mining and metals company.[6] Just after the Second World War, Outokumpu developed this radical, energy-saving innovation in war-ravaged Finland. According to popular accounts (Särkikoski, 1999; Kuisma, 1985; Habashi, 1993, 1998), a major reason why Outokumpu invented the flash furnace was a post-war electricity shortage that threatened to put Outokumpu — which had relied on electric furnace to smelt copper from its eponymous mine — out of business altogether. Instead, Outokumpu's invention proved so successful that at one point, perhaps 60 to 70 percent of world's primary copper was produced using Outokumpu-supplied furnaces. Investigating further, I discovered a voluminous source of material in Outokumpu's archives and old copper metallurgy textbooks, as well as contemporary periodicals and newspapers. Besides Outokumpu's archives, I combed through 58 copper metallurgy textbooks[7] printed between 1846 and 2002, as well as the archive of pre-eminent metallurgy periodical *Journal of Metals.* In total, I was able to collect some 25 000 pages of source material. As the following pages will hopefully show, the case proved to be a rich one indeed, leading me to question many of my original assumptions about constraints and innovation.

Flowing naturally from the choice of primary case study was the focus on *material* and *energy* constraints faced by organizations such as Outokumpu. Prior research exists on the role financial and time constraints play in creativity and innovation (e.g. Hoegl et al., 2008; Weiss et al., 2011, 2014; Rosso, 2014; West, 2002; Baer and Oldham, 2006), and regulatory constraints and their effects have also been studied (e.g. Roediger-Schluga, 2004, 2003; Yarime, 2007). Only few extant works, however, had considered how organizations have used ingenuity to cope with absence of important parts, raw materials or energy supplies. This omission is regrettable, because as I noted above, the grand questions of resource substitution will be ultimately solved or left unsolved by organizations and by individuals working in them. Therefore, understanding better just what happens within an organization that faces a resource constraint should help us to understand what might happen in a society troubled by resource scarcities.

The case selection also helped to better define what I mean by "constraints:" although defining what exactly is a constraint is a notoriously difficult problem (to which I shall return several times during this thesis), the rough definition sufficient for this Introduction is "permanent or temporary incapability to use or do something that might in theory be possible." The difference between constraints and scarcities is another thorny question, to which my chosen solution is to understand constraints as operationalized scarcities: scarcity of some specific resource is a condition that influences the constraints faced by, say, product development teams. In other words, constraints can be said to be signals of scarcity.

[6]My sincere thanks to Dr. Armi Temmes for bringing the case to my attention and loaning me the book in question, Särkikoski's *Flash of Knowledge* (1999).

[7]The full list can be found in Appendix I.

Finally, the case study also informed my decision to focus on *constructed solutions* to constraints and resource scarcities. The choice of words is deliberate: according to Merriam-Webster's dictionary, "to construct" can be defined either as 1) "to build or make something physical;" or 2) "to make or create something by organizing ideas, words and the like". These two definitions cover the interplay of constraints and their solutions that I shall explore further in this thesis. It turns out that the question is not merely about how people and organizations work their way around constraints, but also how they sometimes work the constraints around whatever potential solution they may be favoring, whether deliberately or not. In other words, this study looks not only into how constraints shape technological change, but also how constraints themselves come into being and are shaped by what I call "perceptions of technological feasibility."

Of course, the term "construct" also hearkens back to an important theme within science and technology studies: the notion of social construction of technology (SCOT; see Pinch and Bijker, 1987; Bijker, 1995; Klein and Kleinman, 2002). The research detailed here led me — by training an engineer predisposed to discount "soft" sociological explanations — to conclude that social construction of technology and related concepts such as cognitive technological frames (Orlikowski and Gash, 1994; Kaplan and Tripsas, 2008) play a major and often under-appreciated role in our relations with technology, development of new innovations and in technological and societal change.

1.3.1 An outline of contributions

My hope is that this thesis can contribute to the loosely defined scarcity, abundance and sufficiency (SAS) research, while being useful to broader organization studies and science and technology studies (STS) communities. The research here also presents a new, critical look at the history of flash smelting and hence provides material for historians of metal and minerals technologies, and more generally expands the knowledge about post-war Finland and the time known as "war reparations" or "reconstruction" period. Last but not least, the thesis serves both economic debate and broader society by providing cautionary evidence about how substitution of scarce resources may possibly proceed, and about the probability that constraints and scarcities lead to ingenious innovations.

Scarcity, abundance, and sufficiency (SAS) is an emerging cross-disciplinary research stream that argues that economics and sociology tend to assume scarcity of means as an important premise underpinning much of the research, but rarely stop to consider what scarcity actually means and what is the deeper nature of scarcities (Daoud, 2011; Xenos, 1989). As such, the research stream might best be classified as belonging to critical economic sociology, although it crosses disciplinary boundaries by necessity: after all, as noted by Daoud (2011, 12), diverse set of socioeconomic phenomena, ranging from markets, private property, public good, poverty, power, and action to liberalism, citizenship and time itself "presuppose, hinge on or arise as a causal effect" of scarcities. Scarcity is also the starting point of modern economic analysis (see e.g. classical definition of economics by Robbins, 1932), but as we shall see in the course of this thesis, modern economic analysis is poorly suited for explaining what the scarcities actually are. Another consequence is that mainstream economic analysis is ill-suited for exploring whether there might ever be a situation of (practical) abundance, that is, lack of effective scarcity. As a result, mainstream economic thought tends to downplay some important issues related to scarcity, most notably power relations that determine whether an individual or a society has access to certain goods. This aspect has been famously studied in the context of famines, earning Amartya Sen the Nobel prize in economics for his "entitlement" approach (Sen, 1982, 1986; Devereux, 2001) and spurring further research into food access and its political dimensions (see e.g. Daoud, 2007). However, aside from some forays into the study of water resources (Anand, 2007; Oberkircher, 2011), explorations into the relationship between power and scarcities have been somewhat rare in the recent years. This dry spell could be related to the post-1990 downfall of Marxist economic and sociological analysis, as the questions of power and inequality have been traditional Marxist topics (see e.g. Homer-Dixon, 1995).

This thesis finds that at least in the case studies contained herein, power relations and entitlements have had important influences on the perceptions of scarcities. It also argues that scarcities cannot be fully understood without understanding power relationships, and that entitlement approach could and possibly should be used to analyze how scarcities originate and persist.

In a way, this thesis also helps bridge a gap between SAS and science and technology studies (STS). Scarcities have been long recognized to impact technological change, from the design of automobiles in response to fuel shortages (Hughes, 2004) to how the development of jet engines in Second World War Germany was guided by lack of critical raw materials (Gibbert and Scranton, 2009; Constant, 1980; Giffard, 2016). However, the STS tradition has seen no studies into the nature of scarcities themselves, with the possible exception of an exploratory study by Gibbert and Scranton (2009). I hope that this study might pave way for a broader study of scarcities in technology, and how scarcities persist or even recreate themselves in the perceptions of technologists. Simultaneously, this study is to my knowledge the first to link the SAS and STS literatures and study scarcities from the STS viewpoint.

1.4 Structure of the thesis and an introduction to essays

After this Introduction, chapter 2 will present the theoretical literature review conducted for this study, providing a concise overview of constraints and scarcity literature from organization science, economics, and creativity research. A shorter, separate review in chapter 3 will provide the historical context and position the study in relation to recent research into Finnish economic history and the history of flash smelting, the main case study of this thesis. The main part of the thesis, the four key essays, will follow as chapters 4 to 7. A concluding "semi-essay" in chapter 8 will draw together the lessons learned during the project, while a separate chapter 9 will summarize the findings and implications and provide pointers for future research.

1.4.1 Essay I: A critique of storytelling bias in innovation case studies

This essay, presented at EGOS 2017 conference in Copenhagen in July 2017, takes another look at two case studies repeatedly quoted in organization studies in support for positive effects of constraints to innovation: King's account of creativity during ill-fated Apollo 13 moon mission (King, 1997) and Gibbert and Scranton's study of early jet engine development and supposedly radical innovation developed by German engineers as a result of wartime nickel shortage (Gibbert and Scranton, 2009).

In both cases, a more thorough look into history and details of these cases reveals that the role constraints played was arguably smaller than the case studies imply. The same cases could, in fact, be used as arguments for the importance of prior preparation, not spur of the moment creativity. Furthermore, the jet engine case study in particular shows another example of how constraints may be socially constructed and be influenced by what is technologically feasible. Even though German engineers most probably genuinely believed in nickel shortage, facts concerning Germany's nickel supplies and the importance German high command placed on the development of jet engines, combined with actual manufacturing decisions, strongly suggests that sufficient nickel supplies could have been released in case the nickel-saving solution would not have been feasible. However, precisely because nickel-saving alternative *was* technologically feasible, there apparently was no need to release nickel stocks and hence end the scarcity. In this manner, essay I serves as an introduction to further essays in this thesis that explore the question of constraints even further. In its own right, this essay also contributes to the discussion about the use of historical case studies in management, organizational and innovation studies: it shows how the very same data can be used to tell exactly different stories.

1.4.2 Essay II: Constraints and Ingenuity: The Case of Outokumpu and the Development of Flash Smelting

The second essay of this thesis, co-written with professor Liisa Välikangas and originally published as a chapter in Handbook of Organizational and Entrepreneurial Ingenuity (Korhonen and Välikangas, 2014 in Honig et al., 2014), examines the history and development of flash smelting by Outokumpu and by Canadian mining giant Inco. Going back in history to 1866, the essay argues that the divergent results of earlier constraint-induced innovation studies can be partly explained by accounting for the "prehistory" of innovations in question, and that technological development *prior* to the imposition of constraint plays an important, perhaps decisive role in determining whether constraints accelerate technological change.

The study examines whether, and how, constraints can trigger cognitive and organizational mechanisms that promote creativity, innovativeness and other desirable characteristics. In particular, radical innovations induced by necessity need to benefit from existing "innovation increments." In this view, radical innovation — in a sense of innovations that represent a major conceptual leap from prior art — do not really exist. Instead, such leaps are argued to result from incremental innovation, perhaps in related or even distant fields, that coalesces to produce what may well *look* like a radical leap to those familiar only with a certain field of technology. Technology is here seen to progress according to a process reminiscent of self-organizing criticalities of chaos theory: long periods of relative quiet and incremental improvements can be followed by rapid changes in system state, even without any radical change in system inputs.

This essay underscores how important the availability of existing technological ideas was to Outokumpu's success, and suggested (together with the second essay) that absent such a broad idea base, Outokumpu would probably have chosen another solution to its pressing energy problem. On the other hand, the availability of technological ideas ("components" in the parlance of Arthur 2009) meant that others in the industry were capable of inventing the exact same invention. This raises doubts about whether constraints can ever truly promote technological development, although they can certainly influence technological change and how the latter plays out.

However, while constraints may have relatively little impact on *what* is developed, they can and do influence *who* develops the technologies. In this manner, necessities are the mothers of inventors, not innovations. As such, this study advances our knowledge regarding how creativity and ingenuity are actually influenced by constraints, while arguing for the importance of a long-term view when studying innovation.

1.4.3 Essay III: Tolerating the Intolerable: Flash Smelting of Copper and the Construction of Technological Constraints

The third essay, accepted for publication in *Technology and Culture*, introduces the main case study of this thesis, the development of flash smelting by Outokumpu after the Second World War. It extends the prior work by Särkikoski (1999) and Kuisma (1985; 2016) and provides a slightly different perspective to the process that led to the development of this radical metallurgical breakthrough.

The essay looks at the issue from the company-level perspective rather than from the individual level as in the first essay. In it, I argue that constraints the Outokumpu's personnel were operating under were at least partially constructed by the personnel themselves, and that the concept of "scarcity" or "constraint" can be highly malleable, depending on the circumstances and the purposes of the technologists. In other words, what is important is not the resource endowment or technological possibility as such: what really matters is how the relevant actors *perceive* the scarcities and possibilities. Over the years, Outokumpu used Finland's lack of coal supplies repeatedly as an argument for solutions it found desirable for other reasons as well, but when only a coal-fired furnace would have fitted Outokumpu's expansion plans, the "coal question" was entirely forgotten and its downsides, previously highlighted, were minimized. In fact, Outokumpu went as far as to state in official memorandums that coal could be relatively easily replaced with domestic firewood, if necessary. However, this solution was not examined at all during the post-war electricity shortage: the most probable explanation for this is that the intervening years and Outokumpu's increased technological competency had made flash smelting an attractive, technologically almost mature solution that was worth pursuing.

In this manner, perceived technological possibility influences perceived constraints, while perceived constraints influence perceived technological possibility. The case also highlights the connection between technology and politics: what is politically desirable influences what is seen as technologically feasible, and vice versa.

The essay also contributes to the history of Finland's "war reparations period", a topic that has seen a resurgence of interest lately (e.g. Joukio, 2016; Rautkallio, 2014; Malinen, 2014; Kallioniemi, 2009; Seppinen, 2008). Furthermore, it adds to studies of "techno-nationalism" and its effects (Hecht, 2009; Waqar and Zaidi, 2008; Fridlund and Maier, 1996; Särkikoski, 2011) by arguing that techno-nationalism was a powerful force behind the perception of constraints at various points in Outokumpu's early history. In fact, the essay makes the case that techno-nationalism was a major reason why Outokumpu developed flash smelting in the first place.

1.4.4 Essay IV: Overcoming scarcities through innovation: what do technologists do when faced with constraints?

Finally, the fourth essay, published in *Ecological Economics* (Korhonen, 2018), expands the scope to the level of society, re-introduces the jet engine case study from the first essay and delves deeper into the decisions "technologists" make when confronted by scarcities. Using the concepts of quasi-scarcity (Daoud, 2007, 2011) and the recombinatory view of technology (Fleming, 2001; Arthur, 2007, 2009), I argue that technologists confronting scarcities have essentially three choices: suffer the impacts of scarcities, substitute the existing technology with what is likely an inferior technology, or improve their entitlement to scarce resources through political action. I also argue that some technologies or technological components are inherently more difficult to substitute than others due to interdependency issues.

The problems are likely to be exacerbated in highly efficient systems, since "efficiency" generally requires optimizing systems and optimizing usually means getting rid of resiliency-generating redundancies and flexibilities. This last essay builds upon the idea of perceived scarcities, introduced in the earlier essays, and underscores that we actually perceive scarcities according to the feasibility of *mitigating* or substituting the scarcity. A scarcity is therefore a scarcity in any real social, economic, or managerial sense only if there exists a possibility, however slim, that it can be overcome.

This essay helps to bridge the gap between economics and innovation literature and contributes directly to the sustainability discussion (e.g. Bretschger, 2005; Baumgärtner et al., 2006; Daoud, 2011, 2007; Raiklin and Uyar, 1996; Yarime, 2007) by providing a reason to be cautious about claims that technology can substitute for scarce resources. It also calls for nuance in the scarcity discussion, underscoring that there are different kinds of scarcities. Finally, the essay asks whether scarcity studies might suffer from selection bias: scarcity research might be overly influenced by studies of relative scarcity, which is less problematic to overcome, simply because relative scarcities are easier to overcome and therefore there are likely to be more studies of relative scarcities being overcome through technological substitution.

Chapter 2

Theoretical review

Scarcities and constraints in economy, organizations, and individual creativity

2.1 Introduction to the eclectic mix

As mentioned in the introductory chapter of this thesis, the topic of resource scarcities and their impacts is a broad and wide one. No single work could possibly hope to do full justice to voluminous prior literature, and this thesis is no exception. Nevertheless, this chapter seeks to present an overview of the themes, topics, and important papers in sometimes widely diverging fields that have informed my research.

While the boundaries between the fields that have informed my research are often fuzzy at best, the literature reviewed for this study could be said to fall into four broad categories or research streams. In the following literature review, I've organized these categories according to their unit of analysis, from individuals and teams that actually make the discoveries, to organizations that are usually responsible for commercializing them, and to economies, societies and the broader techno-economic-social system that has to live with the results. This very rough categorization, which cannot avoid some degree of overlap, divides the existing literature roughly to domains of creativity research, organization studies, economics, and science and technology studies.

The selection of works reviewed here is obviously somewhat of an eclectic one. While I've made every effort to be comprehensive, this chapter doesn't present an exhaustive, systematic review. Instead, the following books and papers have been gathered through several years of "snowball sampling" the literature and their citations for clues to further works, and through numerous literature searches at varying times. However, this sampling strategy seemed to work, since by the time I'm writing these lines, new articles bring very few to no new references to works of any significant importance to this thesis.

2.1.1 Definitions

A couple of words about the terminology used in this review are in order. The studies and disciplines reviewed here use somewhat different terminologies and refer to slightly different things with what often are the same or similar words. To avoid confusion, I try to use a consistent terminology throughout this chapter. To that end, I shall refer to *materials* or *material* and/or *energy resources* when I mean resources that are essentially raw materials or "factors of production" for the industries and companies. This differentiates raw material resources, and their scarcities (which are the primary interest of this thesis), from *resources*, by which I mean *organizational resources* such as time, human resources, and funding. Hence, research explicitly studying raw material or energy scarcities or constraints is referred hereafter to as *material* or *energy scarcity* or *constraint(s)* studies, whereas works focusing on organizational resources are discussed as *resource scarcity* or *resource constraint(s)* literature. This differentiation is important, because the organizational and managerial literature on constraints and innovation tends to talk simply of "resources" when referring to organizational resources. While these research findings are likely to be of some use when discussing material and/or energy scarcities, explicit discussion of raw material or energy scarcities in organizational literature is rare.

In addition, the reader should note that while the terms "scarcity" and "(resource or material) constraint" are sometimes used almost interchangeably, they mean slightly different things. In this review, I use the term "scarcity" to refer to larger-scale insufficiency (or perception of insufficiency) of materials, energy, or resources. In other words, "scarcity" is here a system-wide condition. On the other hand, "constraint" is here defined following the general economic approach to social behavior as something that restricts the choice opportunities of an individual or an organization (see Daoud, 2011, p. 16). Therefore, all scarcities manifest themselves as constraints, but not all constraints are scarcities.

This distinction leads us naturally to what are perhaps the most elusive concepts of this review: What are constraints and scarcities? These concepts are so complex and interesting so that they are developed throughout the main essays of this paper and in the concluding chapters. However, for the purposes of this review, we can limit the discussion to scarcities and constraints that are in some manner unexpected in some broadly accepted "normal" or "ordinary" situation. Thus, although it is an axiom of economic thought that all economic decisions are made under conditions of scarcity (because there are always more possible needs than there are resources), and although all creative work is influenced by constraints of some sort, we can safely leave those "everyday" scarcities from the discussion. It is nevertheless interesting to speculate what makes a scarcity a scarcity (or constraint a constraint) in the meaning of scarcity literature, and this is a topic I'm going to address in the essays III and IV in particular.

Note, too, that since this literature review was finalized only after the publication of some of the essays, these definitions and distinctions are not explicit nor consistent across all of the following chapters.

2.1.2 Structure of the chapter

The review is divided into this introduction and three main sections, each reviewing a different level of analysis. The review begins from the highest level, that of economy and society, and continues with research on individual creativity under constraints. These two extreme levels of analysis are followed by what I consider one of the most important levels of analysis for actually understanding how material and organizational resource constraints might influence technology: The level of organizations and firms, the human collectives that are crucially important in the hard work of discovering, developing, manufacturing and propagating potential substitutes to scarce resources.

2.2 Responses to scarcity at industry and economy level

At the highest levels of analysis, that of industries and societies, scarcities, constraints and their effects on innovation are usually studied under the labels of scarcity or regulation. Most of this research is to be found within the economics literature (both mainstream, and, more commonly, in heterodox economics), and the studies are often, though by no means exclusively, conducted using quantitative and econometric methods.

With only little exaggeration, one could say that one of the first and certainly one of the most influential researchers to take note of potential responses to scarcities and constraints was Karl Marx. Marx was famously dismissive of Malthus's notorious claim about the growth of human population inevitably outpacing the available food supply (Malthus, 1798), and considered Malthus to be only an apologist for the *status quo* and the ruling class (Charbit, 2009). While for Marx, the primary response was the overthrow of unjust and class-ridden institutions, he appreciated the potential of technological changes to alter what scarcity meant (Elliott, 1980). However, the late 19th and early 20th centuries seemed to make Malthus obsolete, even though one of the most influential works ever written about the dynamics of scarcity, Jevons's study of the "coal question" (Jevons, 1865) was published in 1865. In the book, Jevons, an economist, explored the implications of Britain's coal use and famously presented the so-called "Jevons paradox": the great increase in efficiency of coal-fired steam engines had in fact resulted to an *increase*, not decrease, in total coal use. This dynamic, currently known as the rebound effect (e.g. Sorrell, 2010; Ayres and Warr, 2009), arises from the fact that more efficient machines are cheaper and therefore more attractive to use in more applications. Jevons's study is probably the first serious examination of a dynamic whereby a technological response to a scarcity — increase in efficiency — may in fact prolong or even exacerbate the scarcity in the long run. (This thesis shall later present another dynamic, a mental rebound effect.)

The scarcity question returned to debate from the 1950s as a new generation of thinkers began to question the sustainability of the modern world. Probably the most influential single work, which was directly responsible for triggering the ongoing scarcity debates, was Ehrlich's Neo-Malthusian *Population Bomb* (Ehrlich, 1968). In it, Ehrlich argued that Malthus was right after all, and that human population would soon (and inevitably) outstrip all possible food supplies. *Population Bomb* tapped into the *zeitgeist* of the times, where potential food shortages and urban unrest were already hot topics. As an example, (another) classic sci-fi dystopia that largely dealt with overpopulation, *Make Room! Make Room!*, was published in 1966, two years before Ehrlich's *Population Bomb* (Harrison, 1966). Ehrlich and his numerous followers made gloomy predictions about inevitable famines ravaging most of the Earth by 1980 (Sabin, 2013), even as the Green Revolution, largely powered by improved access to technologies like fertilizers and systematically improved food crops, was beginning to bring hope to areas Ehrlich and other influential resource pessimists had already condemned to be beyond saving (Hesser, 2006; Sabin, 2013). Such discrepancies between pessimist and optimist predictions have powered a vigorous and often vitriolic debate between people of differing worldviews and experiences. Following Homer-Dixon's characterization (1995), and keeping in mind that any categorizations are bound to be inaccurate and require qualifications, the debaters can be roughly divided into three broad camps:

First, the mainstream (neoclassical) economists, who believe that properly functioning economic institutions, in particular free markets, will provide enough incentives to either conserve important resources or to substitute old resources and resource bases with new finds, new resources, and new innovations;

Second, the Neo-Malthusians, who essentially do not believe in humanity's capability to invent its way out from the limits of natural resources; and

Third, the distributionists, who often follow on Marx's footsteps or were outright Marxists, and think the real problem lies within the unequal distribution of resources and wealth.

2.2.1 The mainstream economic view

Accordingly, the conceptions of how and whether the society might respond to scarcities tend to differ based on how the thinker in question perceives the structure of the world. Most mainstream economists believe in "weak" sustainability, or that almost all kinds of natural capital can be substituted by human-made capital (Ayres, 2007). This optimistic view is the standard fare in most economics textbooks and has resulted to a steady stream of articles and books seeking to prove the argument.

In a way, the argument was already made by Adam Smith, who saw the necessity of obtaining otherwise scarce resources by trading with others as the root of specialization of labor (Friedman, 2005, p. 48). However, classic studies that are more commonly thought to have established the "cornucopian" tradition include Solow's *The Economics of Resources or the Resources of Economics* (Solow, 1974) and Goeller and Weinberg's case study of substitution of mercury (Goeller and Weinberg, 1976), as well as Julian Simon's provocative books arguing that human minds are the "ultimate resource" (Simon, 1981, 1998). Simon, known for winning the famous bet of raw material prices with arch-doomsayer Ehrlich (Sabin, 2013), argued that more humans means *smaller* probability of resource scarcity having any detrimental impacts, as more minds are more likely to come up with wondrous new technologies and solutions. While the resource optimistic view has been somewhat underrepresented in literature lately, it is interesting to note that there are some signs of a resurgence with popular books such as Ridley's *The Rational Optimist* (Ridley, 2011) and Phillips's almost Neo-Marxist tract *Austerity Ecology & the Collapse-Porn Addicts* (Phillips, 2015) arguing, once again, that resource limitations can and will be circumvented through human ingenuity.

With some reservations, the mainstream economics camp can be said to include much of the research on the effects of environmental legislation and other policy instruments designed to alter technological trajectories. The main reason for lumping the sometimes vociferous heterodox critics of neoclassical economics (e.g. Raiklin and Uyar, 1996; Baumgärtner et al., 2006; Tchipev, 2006) to the same camp with the most starry-eyed optimists is because most of the economics literature, both mainstream and heterodox ecological or biophysical economics, is nevertheless optimistic about the possibilities of substitution. This fundamental optimism is best visible in the debate over the so-called "Porter hypothesis." Since Porter and van der Linde published their classic article *Toward a new conception of the environment-competitiveness relationship* in 1995 (Porter and van der Linde, 1995c,b), researchers have tried to find support for or against their radical claim: That stringent environmental regulation — a form of constraint or "artificial" scarcity — can actually *increase* competitiveness if it forces firms and industries to develop novel, profitable innovations in response. The Porter hypothesis was a commendable attempt to reconcile the mutually hostile pro-business and pro-environment positions of the 1980s with a positive-sum strategy that could benefit the environment while accelerating economic growth. Even authors who are critical of mainstream economic theory seem to hope and assume that the hypothesis will eventually be proven true, if only the Holy Grail of "proper" regulatory structures can be enacted (see e.g. Kivimaa, 2008; Mickwitz et al., 2008; Kemp and Pontoglio, 2011). However, despite over two decades of research, empirical support for the hypothesis remains rather weak (Jaffe et al., 2003; Wagner, 2003; Roediger-Schluga, 2004; Frohwein and Hansjürgens, 2005; Lanoie et al., 2008; Ambec et al., 2011). Theoretical studies have confirmed that the Porter hypothesis can hold under certain conditions, but that such situations are likely to be rare in reality (Ambec and Barla, 2002; Mohr, 2002). The fundamental problem is obvious: *If the firms could develop new, profitable innovations, why they aren't already doing it?*

Nevertheless, there is little doubt that scarcities and policy actions like (environmental) regulation can have significant effects on the development and adoption of new technologies (for one example of positive findings, see Brunnermeier and Cohen, 2003). The question is just how effective technological change is in compensating for natural resource scarcities. While the neoclassical economic theory places great faith in technological progress's capability to do so, ecological economics is much less certain whether the potential translates to results (Pearce, 2002). That said, the potential itself has been demonstrated in numerous theoretical models in both neoclassical (e.g. Solow, 1974; Nordhaus, 1992) and ecological economics (e.g. Bretschger, 2005) literatures. For example, Bretschger (2005, p. 148) demonstrated in the journal *Ecological Economics* that technological change can compensate for natural resource scarcities, diminishing returns to capital, poor input substitution, and material balance restrictions, but is limited by various restrictions such as fading returns to innovative investments and rising research costs. A survey of the relevant research by Kemp and Pontoglio (2011) reviewed theoretical, observed econometric, case study, survey-based and mixed-method research that had studied the innovation effects of environmental policy instruments and found that effects depend greatly on the particulars of the policy instruments used. Theoretically, price mechanisms ought to be more effective in promoting novelty and innovation than command and control policies. The theory is supported by econometric studies (although with some reservations due to inherent problems in measuring the stringency of policy instruments, innovation, and all the relevant factors) and by firm surveys, which indicate that the flexibility of the policy instruments increases the odds of "clean" (presumably but not necessarily less resource intensive) technology innovations occurring (Johnstone, 2007). Case and mixed-method study evidence would seem to favor the interpretation that policies that cause constraints or scarcities are more likely to support the diffusion of existing innovations (Christiansen, 2001; Yarime, 2007; Mickwitz et al., 2008), and that the timing of the policy instrument can matter a great deal: political impulses at a wrong time do little good or cost too much time and money to bring about a real change in behavior (a finding I shall attempt to explain later in this review, as well as in Essay IV) (Sartorius and Zundel, 2005). The studies also suggest that firms anticipate the actual regulations to some extent and that the predictability and continuous development are important features in any policy instrument designed to constrain the technologists' choices, and that solutions to the problem may be found outside the sectors affected (Kivimaa, 2008) — another phenomenon discussed later in this thesis. Finally, Kemp and Pontoglio argue that the development of innovations may actually *precede* a policy and even exert pressure on policy-makers (Kivimaa, 2007). This conclusion, also supported by detailed case study research by Roediger-Schluga (2004) and Hoogma (2000), will be of some importance for this thesis.

Finally, it should be noted that according to several observers, neoclassical economics takes scarcities as a starting point of the entire economic analysis (Daoud, 2011; Robbins, 1998). A widely accepted definition of modern economics is that economics is a science that "studies human behavior as a relationship between ends and scarce means which have alternative uses" (Robbins, 1932, p. 15). As Daoud (2007; 2011) and others have noted, this belief in an universal scarcity (as a result of essentially unlimited wants) implicitly places the existence of even a possibility of *abundance* and its study outside the set of possible objects to study (Daoud, 2011, p. 15). In addition, by reducing the study of socioeconomic affairs to a problem of efficient allocation under conditions of scarcity, the neoclassical view does not really help us understand how the various constraints and scarcities arise in the first place (Daoud, 2011, p. 21).

2.2.2 The neo-Malthusian view

Often extremely critical of the cornucopian visions of traditional neoclassical economics, those of the neo-Malthusian bent tend to believe that the capability of human societies to effectively respond to scarcities with any technological developments is in reality extremely limited, a viewpoint sometimes known as "strong sustainability" (Ayres, 2007). Extreme versions of strong sustainability stance are likely to lead to fundamentalist ecological opinions calling for practical abolition of the industrialized society (Shantz, 2003). Such extreme views are rarely held by researchers actually studying scarcity responses, but they have been influential in the environmental movement. More common are critical stances that question the mainstream economic assumptions about sustainability (for just some examples of this voluminous literature, see Vlachou, 2004; Ayres, 2007; Goerner et al., 2009; Meadows et al., 2009; Sorrell, 2010; Sorman and Giampietro, 2013; Fix, 2014).

That said, there is a distinct intellectual tradition of believing that efforts to find substitutes for scarce resources are unlikely to succeed (Ehrlich, 1968; Meadows et al., 1972; Heinberg, 2004). As the name implies, those holding such views are generally (if sometimes unfairly) seen as heirs to Malthus's pessimistic prognostications about the future of humanity, provided that population grows exponentially while agricultural production increases only arithmetically (Malthus, 1798). In a similar manner, today's neo-Malthusians believe that growing consumption of material and energy resources simply cannot be sustained, and that the continuing economic growth will lead to a global disaster relatively soon. Whether the disaster is avoidable or not is a topic that divides the neo-Malthusians, with some believing that with proper (if draconian) policies the global disaster can be avoided (e.g. Heinberg, 2004; Hillman, 2004; Meadows et al., 2009), while others (e.g. Kunstler, 2006; Greer, 2008; Farnish, 2009; Trainer, 2014) think that there is nothing else to do but to ensure that some humans survive somewhere.

If the neo-Malthusians are correct, then the question motivating this study has already been answered: Important material and energy scarcities cannot be overcome with technology. However, analyzing the possibilities of technology is relatively pointless if the starting point is that there are no possibilities, so further discussion of the pessimistic position serves little purpose. More fruitful for the purposes of this study is to note that the strong sustainability position assumes that most if not all important resources are non-substitutable in principle or in practice, and therefore scarcities of important resources are likely to turn into *absolute* scarcities that cannot be effectively attenuated through price mechanism or other market signals. If this is the case, then politics and individual actions that are required for long-term survival of the civilization may be drastically different from what the optimistic mainstream economic view prescribes. If the price mechanism cannot be relied to produce substitutes or curb the use of scarce resources, then strong political control is required; and if strong enough political control is unavailable and/or technology's prospects are uncertain, as many in the current crop of neo-Malthusians seem to assume (see e.g. Heinberg, 2004; Greer, 2008; Farnish, 2009), then the only real choice is between voluntary or involuntary "simplification" of lifestyles and societies. The latter is generally assumed to involve a societal collapse of some kind, and neo-Malthusians are prominent in many "prepper" movements. However, since the simplification is seen as more or less inevitable, discussions of technology and technology's role within this tradition tend to be limited either to denunciations of modern technology, or to discussions about "appropriate" technologies that might be serviceable even after the inevitable simplification. Substitution of scarce resources with technological solutions is, as mentioned previously, largely condemned as futile attempt to preserve the status quo and prolong the collapse.

2.2.3 The distributionist view

Finally, the distributionist thinking does not see scarcities as immutable facts but more as problems of insufficient "entitlement" (Sen, 1982; Devereux, 2001), or insufficient power to control the resource allocation. Distributionists are often critical of the mainstream economic arguments, noting (much as Marx did) that technological change alone does little good unless the power imbalances are corrected (cf. Boyce, 1987). However, many of them are also critical of the Neo-Malthusian position, noting (again, much as Marx did) that talk of inevitable resource scarcity has often been used as a defense of the status quo and as a justification for cutting off all help to the world's poor — much as Malthus's arguments were used in the 19th century Britain (Horner, 1997).

In its purest form, the distributionist argument can be encapsulated in the famous quote from Mahatma Gandhi, *"the world has enough for everyone's need, but not enough for everyone's greed"*. The distributionists believe that there are enough resources to go around and a "proper" distribution of world's resources would effectively end scarcities altogether. Therefore, the scarcities are seen as more or less artificial "quasi-scarcities" (Daoud, 2007, 2011) stemming from lack of entitlement, which itself is a symptom of power imbalances between the powerful and the less powerful (see also Sen, 1982; Devereux, 2001). Scarcities are therefore primarily political problems, not technical or physical ones.

This approach, lately formulated by Daoud as "quasi-scarcities" (Daoud, 2011), is an important addition to scarcity discussion, as it enables us to look beyond stocks of raw materials and the role of technology and bring admittedly very important political factors under the spotlight. So far, the approach has been largely restricted to the study of famines in the footsteps of Amartya Sen's groundbreaking research (Sen, 1982; Daoud, 2007), and to the question of water scarcities (Anand, 2007; Oberkircher, 2011). This is unfortunate, since studies of other types of scarcities might benefit from the wider use of distributionist approach.

However, the pure distributionist approach is just as vulnerable to criticism as the previous two approaches, and a conclusion of this brief review of the "sterile three-cornered debate" to paraphrase Homer-Dixon (1995) should probably be that all three approaches have something to offer (see also Lähde, 2013, for a discussion about various conceptions of constraints and scarcities).

The mainstream economic approach shows that at least sometimes, price mechanisms and other market signals work, substitutes can be developed, and scarce resources conserved via primarily technological improvements. On the other hand, the neo-Malthusian approach provides a welcome counterweight to the most optimistic claims and questions whether all resources are truly as substitutable as the optimists claim. Finally, the distributionist approach serves as an useful and important reminder that the issue of scarcities goes beyond easily measurable and quantifiable issues, and that politics are still central to the question of how the humanity should live within the means of its homeworld.

Understanding at least the fundamentals of each approach is valuable to the study of scarcity-induced innovation, since many works purpotedly examining e.g. individual or, in particular, organizational creativity under constraints are deeply influenced by one of these economic traditions. At the moment, most works in organizational literature, for example, are heavily indebted to mainstream economics view and tend to assume quite optimistically that humans can and will overcome any constraints — possibly with better results as a consequence. While there are some organization-level works that have highlighted the political and socially constructed nature of constraints (e.g. Lombardo and Kvalshaugen, 2014; Rosso, 2014; Walker et al., 2014), the study of constructed constraints is only beginning, and to my knowledge there are no studies of organizational or individual innovative behavior under conditions approximating absolute scarcity, unless certain "frugal" innovation studies can be counted as such (see e Cunha et al., 2014).

2.3 Individual and team level constrained creativity studies

At the other end of the scale from entire humanity, national economies and whole industries sits the important decision-maker: an individual human being. Ultimately, it is individuals who develop, or fail to develop, the ideas that may spring from scarcities and constraints, and therefore understanding how constraints and scarcities influence individuals is a requirement for a deeper understanding of how, and whether, scarcities can foster technological change.

At individual and team level, the effects of scarcities and constraints have been studied mostly by researchers with a background in psychology or cognitive sciences. In these fields, the study of creativity — usually defined as "the generation of ideas that are both novel and useful" after Sternberg and Lubart (1999) — has risen in prominence since the 1980s, and resulted to a wealth of studies on the antecedents of creative behavior.

Initially, many influential researchers argued that creativity requires "creative freedom" (e.g. Amabile, 1983; Amabile and Gryskiewicz, 1989; Damanpour, 1991; Amabile, 1996). Typically, this was interpreted to mean that constraints of *any* sort would be detrimental for creativity and, by extension, for innovativeness. However, such blanket statements soon gave way to more nuanced approaches. The universally negative role of constraints was quickly challenged, particularly in research by Finke, Ward and Smith (Finke et al., 1992, 1995) and Ward (Ward, 1994, 2004; Smith and Ward, 1993). Finke, Ward and Smith (1992) argued that individual creativity is actually enhanced when it is limited by constraints, at least when compared to "blank slate" of unbounded opportunities. Such research led to the "Geneplore" model of creativity (Finke et al., 1992, 1995), where creativity is seem as a highly constrained process that is influenced by existing knowledge frameworks, just as any task where categories and concepts are involved. The Geneplore model suggests that individuals retrieve from memory existing knowledge frameworks, so-called "pre-inventive structures." These are then recombined given the task at hand, and its constraints. Going further, Ward (1994) developed the "path of least resistance" theory. According to this theory, when people are confronted with a problem, the easiest and therefore most common approach would be to use a known solution. However, if the known solution becomes infeasible due to constraints, more creative solutions are more likely to emerge.

Subsequently, the path of least resistance (POLR) theory has been supported by numerous experimental laboratory studies, where the restriction of choices available to test subjects tended to correlate positively with assessed creativity of outcomes (Goldenberg et al., 2001; Moreau and Dahl, 2005; Dahl and Moreau, 2007; Moreau and Dahl, 2009; Sellier and Dahl, 2011). The role and mechanisms through which constraints operate have also been elaborated further in theoretical, conceptual, observational and case studies (e.g. King, 1997; Stokes, 2001; Stokes and Fisher, 2005; Yokochi and Okada, 2005; Stokes, 2007, 2008, 2009, 2014; Rosso, 2011, 2014).

From theoretical viewpoint, one of the strongest arguments for potential positive effect of constraints comes from research that conceptualizes creative work as a search for solutions in a problem space (Simon, 1962, 1969; Newell and Simon, 1972; Greeno and Simon, 1988). Typically, the full problem space is envisioned as a the every possible combination of everything, a space vast beyond imagining. If creative activity is now thought to involve search and evaluation of potential ideas in this space, it is obvious that successfully searching through the *full* problem space (all possible combinations of everything) is simply an impossible task in any limited time. Constraints can now be envisioned to "lock" some possible variables, and therefore limit the problem space to more manageable dimensions (Reitman, 1965). This view has informed and inspired the works of numerous researchers in many different fields. Among these, some examples of researchers whose works deal with scarcity, constraints or technology include Parayil and Govindan (1991), Katila, Ahuja and Shane (Katila and Ahuja, 2002; Ahuja and Katila, 2004; Katila and Shane, 2005), Fleming (2001) and Schilling (2011). These studies usually define constraints quite broadly, and even emotions have been considered as constraining and facilitating factors for individual creativity (Yang and Hung, 2015). However, the empirical works tend to focus on time constraints.

However, this "one-sided" view of constraints as merely limiters of problem space has been challenged by Stokes through her research on the role constraints have played in creativity and novelty in the works of painters such as Monet (Stokes, 2001), Beckmann and Guston (Stokes and Fisher, 2005), and Modrian and Klee (Stokes, 2008). Stokes argues that constraints come in pairs: when solving what Stokes calls "novelty problem" (Stokes, 2001; Stokes and Fisher, 2005; Stokes, 2007, 2014), one of the pair precludes or limits search among unsurprising, tried-and-true responses just as "one-sided" theory suggests, but in addition, the second of the pair promotes or directs search among surprising, untried responses as well. As an example from art world, the development of Pop Art style involved (among other constraints) an aversion of improvisation dominant in then-current "hot" painting style, Abstract Expressionism. Precluding improvisation then simultaneously promoted pre-planning, as seen in the works of Roy Lichtenstein and Andy Warhol. Stokes believes that these lessons apply to technological and organizational creativity as well. Other examples of constraint-influenced creativity research using art as a case study include Candy (2007) and Yokochi and Okada (2005).

In another case study, Onarheim (2012) specifically studied how constraints, defined as "limitations or restrictions for what can or cannot be done in the design process, and for what the design process should fulfill" (Onarheim, 2012, p. 324), both limited and enhanced engineering design. In a longitudinal study of a major international producer of disposable medical equipment, Coloplast A/S, Onarheim observed that constraints can indeed not only limit but also enhance the outcomes of engineering design, and suggested four practices that actors generally resort to when they search for design solutions but bump against constraints. The first observed practice is “black boxing”, where certain constraints are treated as unchangeable, and essentially ignored in order to focus on more crucial constraints. Second, actors may practice “removal”, or temporary setting aside of highly fixed constraints to see if new, previously overlooked solutions can emerge. Third is the practice of “introducing”, or identifying and adding implicit constraints to make the problem clearer (see also Hargadon and Sutton, 1996; Stokes, 2006; Rosso, 2014, for examples of such practices). Finally, the fourth practice is “revision”, where constraints that stood in the way of a creative solution are retrospectively reviewed to see if they can be revised or redefined.[1]

In short, considerable theoretical and conjectural evidence exists suggesting that constraints can be beneficial for individual creativity. With the exception of some case studies by Stokes and others (e.g. King, 1997; Rosso, 2011, 2014), most actual evidence in favor of this hypothesis comes from laboratory studies of individual creativity. Generally speaking, these studies compared creative output between experiments where either creative inputs or required outputs were constrained, and control experiments where no such constraints applied. The outputs were assessed by external experts on dimensions such as innovativeness or creativity. In such settings, the innovativeness and creativity of resulting solutions was judged to improve as a result of input resource constraints, that is, what can be used to solve the problem (Goldenberg et al., 2001; Moreau and Dahl, 2005; Dahl and Moreau, 2007; Sellier and Dahl, 2011), and as a result of time constraints - provided that these were not too strict (Ridgway and Price, 1991; Burroughs and Glen Mick, 2004).

Due to understandable practical limitations on experimental design and the focus of these studies, many of the tasks performed in these experiments represented relatively generic, early stage concept development that can be performed by a large group of test subjects. Therefore, the tasks could not require too specialized subject matter expertise: for example, one of the tasks was “design a [concept for a] toy for children using only specific [geometrical] shapes” (Goldenberg et al., 2001). Other experiments have focused on creativity in relatively open-ended DIY tasks, such as knitting a scarf (Dahl and Moreau, 2007; Sellier and Dahl, 2011). While the overall findings

[1] Onarheim’s observations match closely my own experiences from product design and development.

— that limiting the search for ideas to a more confined set provides a focal point for search for solutions, helps avoiding "choice paralysis", and may therefore help creativity (Finke et al., 1995; Perkins, 1981; Weisberg, 1992) — would seem to be reasonably generalizable, it does not necessarily follow that the results can be used to draw solid conclusions about the effects of constraints on professional research and development projects and their outcomes. In particular, there seems to be a potential danger in conflating creativity and novelty with qualities required for successful innovation: important as they are, creativity and novelty of a solution are not the only determinants of successful innovation, and may even be detrimental in some cases.

Nevertheless, these experiments are often the closest that a major research stream has gone to studying the effects of material or energy constraints in individual creative activity. They are also often cited in research on team and organizational innovation in support of argument that constraints can induce innovation (e.g. Hoegl et al., 2008; Weiss et al., 2011, 2014), and as long as their limitations are kept in mind, such studies provide evidence that suggests constraints play a more complicated role than merely limiting creative freedom of individuals.

2.4 Organizational innovation under constraints

The study of constraints in organizational innovation generally falls under the rubric of my academic home field, organization studies. Studies at this level are particularly important for understanding the mechanisms of how resource constraints influence innovation, since the actual development and adoption of innovations that may substitute for scarce resources tends to happen at this level.

During the last decade or so, researchers coming mostly from organizational and innovation research backgrounds have argued that constraints can actually act as promoters of innovation and novelty (e.g. Gibbert and Välikangas, 2004; Gibbert et al., 2007; Gibbert and Scranton, 2009; Hewitt-Dundas, 2006; Hoegl et al., 2008; Weiss et al., 2011; Banerjee, 2014; Troilo et al., 2014; Weiss et al., 2014; Keupp and Gassmann, 2013; Paeleman and Vanacker, 2015; Bicen and Johnson, 2015). The fundamental ideas are similar to what research on individual creativity has developed: Under proper conditions, constraints can act as "focusing devices" (Rosenberg, 1969) that help to focus the organizational and individual efforts to a specific goal. The idea can be related to the concept of bottlenecks and “reverse salients” (Hughes, 1983, 1987) in the history of technology and science and technology studies, where the concept of reverse salient has been used to describe a sub-system of a technological system that delivers insufficient performance and therefore limits the performance of the whole system (Shields, 2007; Dedehayir, 2009). As a result, reverse salients often attract attention from developers of technology, and may possibly lead to breakthroughs as a result (Hughes, 1983; Dedehayir, 2009).

However, the intellectual roots of most of the organizational research are different. These studies and the “less is more” school of thought can be seen to have originated from critique of classic resource-based view of the firm (Paeleman and Vanacker, 2015). Even though Cyert and March wondered in their very influential *A Behavioral Theory of the Firm* (Cyert and March, 1963) already in 1963 whether innovation was stimulated by constrained or slack resources, the classic resource-based view (RBV) literature explained the differences in firm behavior and success to follow from the heterogeneous bundles of resources the firms possessed (Barney, 1991). In the resource-based view, an important determinant of innovation is the share of unallocated “slack” resources relative to total bundle of resources. This resource slack is often seen as a necessary precondition for successful innovation projects (Mishina et al., 2004). As a consequence, resource-based view tends to lead to the thinking that more resources is better. Other organizational research streams reinforced the message: for example, in operations research, the fundamental premise is that constraints to choice always interfere with optimum resource allocation and are therefore undesirable (Kolisch et al., 1995). Of course, decades of organizational research aren’t wrong per se: Ample resources *are* a very possible source of competitive advantage, and often extremely important for more exploratory innovation (March, 1991).

Importantly for research and practice of innovation, this more-is-more message has been repeatedly echoed in literature on new product development and innovation management, where so-called “fuzzy front end” approach has seen considerable success from about mid-1990s (e.g. Koen et al., 1996; Khurana and Rosenthal, 1998; Reid and De Brentani, 2004; Koch and Leitner, 2008). First popularized through experiences in automobile design and extensive studies conducted at large car manufacturers (e.g. Fujimoto, 1997; Thomke and Fujimoto, 2000), this approach emphasizes the importance of creative freedom (in a parallel to aforementioned research on individual creativity), particularly during the early stages — the “fuzzy front end” — of innovation process. At this conceptual stage, creativity should be encouraged and any limits to ideas should be discouraged (Karniel and Reich, 2011). Limitations such as manufacturability or even feasibility of these ideas should only be considered in the next stages of this rather linear process, where "degrees of freedom" available to developers decrease linearly as the innovation process advances from concepts towards final product (Reid and De Brentani, 2004).

Unsurprisingly, other researchers have expressed their doubts about these prescriptions. In view of the critics of resource-based view, slack resources are more likely to lead to inefficient resource use (Baker and Nelson, 2005; Katila and Shane, 2005). In particular, the innovation successes of entrepreneurs are often explained to result from the efficiency- and ingenuity-promoting resource scarcity that entrepreneurs usually face (Starr and MacMillan, 1990; Nohria and Gulati, 1996; Garud and Karnoe, 2003; Baker and Nelson, 2005; Banerjee, 2014). One of the results of such studies is the emergence of "bricolage" research, which studies how people (and resource-strapped people in particular) show ingenuity in co-opting or otherwise acquiring resources that they wouldn't normally have access to, and then recombine these and existing resources in clever ways to produce novelty and valuable products or services (Baker and Nelson, 2005; Katila and Shane, 2005; Schuster, 2006; Duymedjian and Ruling, 2010; Rogers, 2012; Halme et al., 2012; Houtbeckers, 2013). Bricolage is an important concept especially in entrepreneurship research (Senyard et al., 2009), and it, alongside other resource scarcity concepts, has been recently invoked to study and explain the rise of so-called "frugal" innovation in developing countries (e.g. e Cunha et al., 2014). However, while the concepts are related, bricolage refers more to novel combinations of existing components, whereas frugal innovation might perhaps be better understood as innovating when affluent customers are scarce (e Cunha et al., 2014).

Likewise in product development and innovation management research, there have been efforts to argue for more diverse role for constraints (see e.g. critique of "unbounded" fuzzy front end approach by Arrighi et al., 2015). At the same time, there is growing recognition that strictly linear product development processes are rare, particularly outside large firms and major development projects, and that considering constraints or even constraining available options from the very early ideation stage may help produce better designs. However, research in this stream has been relatively silent about organizational responses to societal scarcities, such as lack of some important raw material. Nevertheless, a sign of an increasing popularity of the "constrained innovation" or "less is more" school of thought is the appearance of no fewer than four relatively recent special issues dealing with the topic in *Long Range Planning*[2], *Journal of Product Innovation Management*[3], *Organization Studies*[4]; and *Creativity and Innovation Management*[5].

These studies seem to be coalescing into a part of broader "organizational ingenuity" (or just "ingenuity") research stream (Lampel et al., 2011; Honig et al., 2014). Ingenuity can be defined as "the ability to create innovative solutions within structural constraints using limited resources and imaginative problem solving" (Lampel et al., 2014, p. 465). As Lampel, Honig and Drori note in their introduction to the special issue of *Organization Studies* (Lampel et al., 2014), ingenuity in face of limited resources has been an important part of the capitalist ethos since the early 1800s. The image of special geniuses overcoming better equipped rivals has been particularly influential in the United States, from where it spread to other countries following the success of American brand of capitalism. However, the rise of industrial laboratories and industrialized innovation during the first half of the 1900s caused the pendulum to swing against this genius-worship and, as a consequence, against the idea that limited resources can spur individuals to great deeds (Lampel et al., 2014). The recent mushrooming of studies arguing essentially the opposite may be a sign that the pendulum is moving towards the other extreme, or that the thesis and and the antithesis are producing a synthesis that acknowledges the role for both constraint-induced creativity and the hard, routine slog of industrialized innovation.

It is worth emphasizing at this point that the vast majority of this literature, with few exceptions that I shall detail separately below, focuses on organizational resource constraints. For example, from the four special issues mentioned earlier, one (*Journal of Product Innovation Management*) is explicitly focused on financial constraints, and in the rest, discussion of non-organizational constraints is rare. Caution is therefore advised before applying their conclusions to the material and energy constraint question that is the focus of this thesis. The mechanisms how constraints may stimulate (or inhibit) innovation are likely to be broadly similar in both cases, and one could argue that all constraints can ultimately be

[2] Issue 6/2004, with articles by Boisot and MacMillan; Dougherty and Takacs; Gibbert and Välikangas; Grand et al.; Karim and Mitchell; Roos et al..

[3] Issue 2/2014, with articles by e Cunha et al.; Gibbert et al.; Rosenzweig and Mazursky; Senyard et al.; Stokes; Troilo et al.; Weiss et al..

[4] Issue 4/2014, with articles by Dolmans et al.; Kannan-Narasimhan; Lampel et al.; Lombardo and Kvalshaugen; Rosso; Walker et al..

[5] Issue 2/2015, with articles by Arrighi et al.; Bicen and Johnson; Caniels and Rietzschel; Fay et al.; Marguc et al.; Roskes; Stetler and Magnusson; Yang and Hung.

reduced to organizational resource constraints. In theory, dearth of some critical raw material would simply mean that an alternative needs to be found by the allotted staff, within budget and in time — and that time and staff available are themselves a function of budget. While such reductionism may sometimes be fruitful, reducing all constraints to organizational resource constraints risks abstracting out possibly important details and differences in how individuals, organizations, industries and societies respond to material scarcities and constraints. For example, while a development team might be able to petition the top management for more money in case the team believes it can't finish a project with the allotted resources, who do they approach if a material required for the project is unavailable? And in which cases material constraints result to a firm making a budget available for replacement, and when the firm just suffers the privations?

With this caveat in mind, the existing resource-constrained innovation literature does provide some interesting insights. The common trait in these studies is that they seek to highlight solutions that are not just adequate, but "ingenious" in that they exceed the expectations (after Lampel et al., 2014). In other words, studies of constrained innovation focus on the possibility of constraints leading to innovations that are much better than merely adequate stop-gap solutions. As may be expected from research with strong links to management and businesses, these studies are almost without exception adhering closely to the optimistic mainstream economic thinking discussed in an earlier section of this review. In almost all organizational literature where the innovation effects of constraints are discussed, constraints and perhaps even global scarcities are seen either as disruptions to the desirable status quo, or as a possible source of distinctive competitive advantage for firms smart enough to leverage them. Nevertheless, despite their emphasis of organizational resource constraints, ingenuity studies can arguably serve as micro-level testbeds for the aforementioned Porter hypothesis (Porter and van der Linde, 1995c): are there circumstances where organizations could reliably come up with competitiveness-enhancing improvements if prodded by constraints?

2.4.1 Organizational resource constraints and innovation performance

The general consensus emerging from the team- and organization-level studies seems to support the high-level findings reported in the earlier section of this review: Organizational resource constraints can sometimes prod organizations to develop something they probably wouldn't have developed otherwise, but this is by no means an universal rule. However, the idea that slack resources are essential for innovation is not well-supported either.

Whether constraints result to an improvement in innovation performance seems to depend on attitudes, team dynamics and approaches used by the research and development teams. For example, Hoegl, Weiss, Gibbert and Mazursky (Hoegl et al., 2008; Weiss et al., 2013) propose that perceived financial constraints and innovation project performance are not systematically correlated, and find empirical support for the proposal (Weiss et al., 2011). Further, the group has developed a theoretical concept of *resource elasticity* to explain how varying degrees of perceived organizational resource adequacy influences innovation project performance. In their model, team's competence, motivation and focus, cohesion, and successful (or perhaps lucky?) leveraging of relevant skills and resources matter more than the perceived or actual resource endowment itself. Significantly, these studies emphasize that what matters is the *perception* of constraint, not some actual, measurable resource inadequacy — which is a remarkably difficult concept to define or operationalize in any case. These intuitively very reasonable claims are explained in detail by Weiss et al. (2013), using findings from individual creativity and cognitive research. Weiss et al. claim that innovation teams that tend to perceive fewer resources as adequate are more likely to show signs of resourcefulness, compared to teams that fall into a "victim mentality" of inadequate resources.

These claims and the idea that the effects of constraints ought to be evaluated in a more nuanced manner find empirical support in studies by Rosso (2011; 2014), whose extensive field research studied how constraints can both inhibit and enhance the creativity of research and development teams depending on the constraint and the dynamics of the team. Rosso found not only that the team climate and attitudes matter, just as Hoegl, Weiss, Gibbert and Mazursky predicted, but also that there is a difference between different kinds of a constraint, which he named *process* and *product* constraints. Process constraints constrain how the work was to be done, i.e. time, equipment, human resources and money available to the development team. Product constraints, on the other hand, constrained the intended or expected outcomes of the work. In Rosso's study, these were product requirements, customer and market needs, business needs, and intellectual property issues the team had to take into account when developing a new product. Of these, the most commonly perceived as salient constraints influencing the work were time constraints (identified as such by the majority in all four teams studied) and product requirements (identified by the majority in two teams). As an example how even the same constraints can have quite different effects, Rosso found that process constraints can hinder team creativity when they reduced experimentation and intrinsic motivation, but enhance it if they provoke motivation, team cohesion, or novel approaches. Similarly, product constraints served to enhance creativity when they provided focus and structure, but inhibit it when they reduced the perceived challenge or promoted the status quo.

More evidence for the ambiguous nature of constraints comes from observational research by Lombardo and Kvålshaugen (2014), which sees constraints not as external factors but as inextricably intertwined parts of all creative action. In their view, constraints are therefore implied every time some creative action is performed, an echo of philosopher Cillier's notion that "boundaries are simultaneously a function of the activity of the system itself, and a product of the strategy of description involved" (Cilliers, 2001, p. 141). Writing in the ingenuity special issue in *Organization Studies*, Lombardo and Kvålshaugen find that there are regularities in how development teams and practicioners within teams use constraints creatively, as a tools to challenge and "shatter" the status quo. In this manner, constraints can serve as points of leverage instead of merely hindering organizational creativity and innovation performance.

Another *Organization Studies* special issue article worth treating in more detail here is the paper by Dolmans et al. (2014), where the researchers focused on entrepreneur's perceptions of resource availability. By studying three Dutch high-tech firms, two successes and one bankruptcy, the authors concluded that resource constraints ("resource positions" in the original) are highly transient and imaginatory in nature. Entrepreneurs were found to perceive resource availability in relation to demand, and the researchers concluded that "fixed" measures of resource availability were unlikely to be satisfactory. As can be seen, the theoretical idea of resource constraints being more a matter of perception than measurable fact (e.g. Hoegl et al., 2008; Weiss et al., 2014) is therefore quite well supported in case study research.

These findings dovetail with the aforementioned bricolage research stream, which has studied how resource-strapped organizations and individuals can nevertheless come up with innovative — perhaps ingenious — solutions to practical problems. One of the studies to explicitly link constraints and bricolage is by e Cunha et al. (2014), who conducted a literature search on the role of resource scarcity on product innovation. The focus of this paper, published as a part of *Journal of Product Innovation Management* special issue, was on three forms of scarcity, namely lack of time, material resources, or affluent customers. As such, the literature surveyed included "bottom of the pyramid", "frugal" or "jugaad" innovation research that studies how the world's poor innovate, sometimes in conditions of extreme scarcity. The paper in fact defines frugal innovation as "product innovation when affluent customers are scarce" (e Cunha et al., 2014, p. 206). While the authors claim that frugal innovation can enable a true "clean sheet" approach to product development and help with cost discipline, they admit that empirical work on frugal innovation, aside from a few case studies, is practically nonexistent. Bricolage studies are also an emerging research stream, and studies like Garud and Karnoe's case study of technology development by resource-strapped and resource-endowed wind turbine developers (Garud and Karnoe, 2003) would be welcome complements to the constrained innovation and ingenuity research. In their study, Garud and Karnoe find that greater resource endowment allowed rich U.S. wind power manufacturers to make greater bets with the technology, but the results of such an haphazard strategy were poor compared to Danish developers, who had to proceed cautiously and incrementally due to their limited resources. However, research also claims that bricolage should be only a temporary solution, and growing organizations must eventually reject widespread bricolage in order to grow into mature companies and take advantage of profit opportunities (Baker and Nelson, 2005).

2.4.2 A brief digression: Recombination as a source of innovation

Bricolage research has also identified the importance of *recombinations* for creating innovative outcomes. For example, after Senyard et al. (2014) interviewed individuals from over 600 firms, they concluded that bricolage — "making do by applying combinations of the resources at hand to new problems and opportunities" (Baker and Nelson, 2005, p. 333) — provides an important pathway to innovation for resource-constrained firms. This pathway relies on recombining existing resources and objects that others may not value in new ways (Baker, 2007). Senyard et al. go on to propose that variations in the degree to which firms are able or willing to engage in bricolage could explain the differences in innovativeness under resource constraints, at least for new firms.

The idea that recombination lies at the root of innovation is not new, and a brief digression to this theory of technology is in order here. The idea that all technologies are, indeed have to be, (re)combinations of existing components is an intuitively appealing one, and its expression in research about technology can be traced to Schumpeter and beyond (Schumpeter, 1934; Ogburn, 1922). Recent years have seen a resurgence of research into the topic (e.g. Fleming, 2001; Fleming and Sorenson, 2001; Frenken, 2006; Arthur, 2007, 2009; Murmann and Frenken, 2006; Savino et al., 2015; Strumsky and Lobo, 2015), and at the moment the recombinatory theory of innovation seems to be widely accepted among scholars of technology. One of the great benefits of this theory is that it gives technologies an "interior," to quote Arthur (2009), and therefore allows us to open the "black box" of technology (see Rosenberg, 1982) for deeper analysis of what actually happens when a technology is developed or modified.

One of the implications of this thesis, discussed in Essay IV in particular, is that our thinking about technologies and their possibilities could be much improved by using more widely the recombinatory theory or some other theory of technology that provides similar detail about the inner workings of technological systems. For the purposes of reviewing the literature on scarcities and constraints, it is however enough to note for now that inputs and outputs of a technological system can also be thought of as components to the system, and that scarcities and constraints often affect the availability of various sources of inputs, components, or sinks for undesirable outputs (waste) in particular.

2.4.3 Studies of non-organizational constraints

As mentioned above, the great majority of organizational, managerial, and innovation-related studies of resource constraints have been concerned mostly about what I termed "organizational resources" in the introduction to this review chapter. While these works usually acknowledge the potential existence of other sorts of constraints, theoretical and empirical research into their effects is uncommon — although there is significant overlap in some research, such as aforementioned studies by Rosso (2011; 2014) and Lombardo and Kvålshaugen (2014). As already mentioned, Rosso found that alongside organizational "process" constraints, "product" constraints, i.e. intended or expected outcomes of development work, particularly product requirements, could have salient impacts on innovation outcomes if they provided focus and structure to the task. Lombardo and Kvålshaugen's research was also covered earlier, but it is worth noting here that they, too, looked into both "process" and "product" constraints (to use Rosso's terminology). The latter were in this case various political and technical constraints.

Nevertheless, some studies have looked more or less explicitly into non-organizational constraints as a factor in innovation team performance. One of the more important studies in this area is the case study of jet engine development by Gibbert and Scranton (2009), which looks (among other scarcities) into wartime nickel shortage as an explanation for the German development of a specific jet engine-related innovation. Similar conclusions have been drawn by earlier historians of technology such as Schubert (2004) and von Gersdorff (2004), but, as I explain in Essays I and IV of this thesis, these claims may be slightly exaggerated, and the nickel scarcity might be best understood as insufficient entitlement or quasi-scarcity, to use the terms introduced in the earlier section of this review.

In a quite different setting, Walker et al. (Walker et al., 2014) studied the embryonic solar energy industry in Ontario from early 2009 to mid-2012s. The constraints in this case were institutional, such as lack of access to electric grid, a major hindrance to the adoption of solar power. Again, these scarcities can be seen as examples of insufficient entitlement. The study found that strategies the constrained firms used to cope with the constraints could be framed as either compliance, challenge or escape (following Oliver, 1991), and that firms developed these strategies over time in a sequence of strategic responses.

As can be seen from this short list, studies that consider non-organizational scarcities or constraints yet have an explicit organizational focus are somewhat rare. Partly for this reason, worth mentioning in this section of the review are also certain historical accounts and case studies that may not come from organizations management or economics research tradition but nevertheless shed light into how organizations and innovation teams work when faced with non-organizational constraints. As noted in the introductory chapter of this thesis, a major impetus for my research was Särkikoski's excellent historical account of the development of flash smelting of copper by Finnish copper producer Outokumpu (Särkikoski, 1999). This study detailed the process that led from an electricity scarcity to a very energy-efficient smelting furnace and beyond, a story that is returned to in greater detail in Essays II and III of this thesis. Of note due to its connection to copper industry is also LeCain's brief historical study of the early 1900s development of electrical pollution scrubbers as a response to arsenic pollution of copper smelters (LeCain, 2000).

Besides these works, another detailed history of development task under conditions that can be fairly said to have at least approximated scarcity is Shnayerson's popular but meticulous account of the development of General Motors' early 1990's electric car, the Impact (Shnayerson, 1996). The Impact was a part of early 1990's rush for electric vehicles as a response to California's 1990 Zero Emission Mandate, and the Mandate's effects and eventual demise have also been studied in Hoogma's detailed case study (Hoogma, 2000), also mentioned in the earlier section of this review. Another previously mentioned work containing some useful material on innovation teams and organizations is Roediger-Schluga's study of Austrian chemicals industry as a response to tightened volatile organic compounds (VOC) emissions (Roediger-Schluga, 2004). Finally, the study of ingenuity expressed by flight engineers of Apollo 13 moon mission (King 1997, also discussed in e.g. Kranz 2000) also provides some insights into how creative teams might operate, although the reader is directed to the Essay I of this thesis for another take on the subject.

Finally, worth mentioning for the sake of completeness are studies into *knowledge constraints*, whose effects have been studied sporadically as a part of broader knowledge and innovation research stream. The most recent example to come to my attention is a study by Rosenzweig and Mazursky (2014), who looked into knowledge constraints at an industry level in the United States, assessing in a longitudinal survey covering over 175,000 U.S. patents the importance of different types of knowledge sources to innovation, and whether knowledge constraints affect technological innovativeness. Their somewhat counterintuitive finding is that trade-related knowledge constraints are largely positively associated with the innovativeness of technological output.

2.5 Summary

In this chapter, I've provided a review of the literature that has theoretical or empirical bearing on the main question motivating this thesis: should we, or should we not, expect that scarcities beget innovation that permits us to live with the scarcity without significant decrease in our well-being?

In response, I've reviewed studies ranging from economics to individual creativity, with organizational ingenuity in between. While this review is not a systematic and most likely not a comprehensive one, I nevertheless hope that it will provide an overview of the main positions, research traditions, and arguments used.

In a summary, what this review shows is that the starting point for the study of scarcities/constraints and innovation has most often been heavily influenced by mainstream, largely neoclassical economic thought. From this starting point, scarcities and constraints were previously seen as largely external factors that hindered innovation and technological progress by limiting the choices of technology developers. While the study of scarcities has evolved lately, and the potential benefits of scarcities in focusing and promoting creativity are now also recognized, the discussion about scarcities and technological responses is still dominated by the neoclassical, techno-optimistic paradigm. Almost without exception, the organizational literature sees scarcities either as hindrances to profitable operation, or as potential sources of competitive advantage. Even the critical voices within, say, ecological economics community tend to be rather moderate and optimistic, assuming that if only the *just right* recipe of policy measures can be found and implemented, scarcities will promote "green" innovation and economic growth.

On the other hand, more stringent critics of the business as usual see technology more as a source of problems in the first place. In the tradition that believes the collapse of industrialized societies is just a question of time (and likely sooner rather than later), technology's possibilities to substitute or ameliorate scarcities are generally discounted, and thinkers of the neo-Malthusian bent tend to state explicitly that the coming collapse or simplification *will* cause a significant impairment in the material standard of living. While studies of collapse-proof "appropriate technology" are undoubtedly interesting, they are somewhat beyond the scope of this thesis and unfortunately I had to leave them out from this review. Nevertheless, there is little research in organizational implications of absolute scarcities, except, as mentioned above, possibly in the frugal innovation literature.

Somewhat better represented in organizational literature at least are studies that follow the distributionist thinking and talk about the political roles constraints can play. However, these studies are still in the minority. This approach could well prove to be fruitful in the future.

With these caveats in mind, the studies point to clear conclusions: constraints and scarcities can sometimes promote creativity and innovativeness, but they do not do so reliably. Constraints and scarcities are not alike, and it would be a simplification to talk of them in simplistic terms. What is needed is a nuanced approach to constraints and the situations where they are encountered. The rest of this thesis shall attempt to provide one nuanced view into the issue.

Chapter 3

Historical review

The historiography of flash smelting and "war reparations" period

3.1 The historical context

The key purpose of this short chapter is to provide a concise survey of the prior historiography of flash smelting, the main case study used in this thesis, and provide an overview of previous research into post-war period of Finland's history, often known as the "war reparations" or "reconstruction" period. Another short overview seeks to place the secondary case study — the development of early jet engines — into its historical context. This overview, cursory as it is, should help the reader to position this study into the broader context of historical research.

This chapter is organized into two main sections. The first deals with research into Finland's war reparations period, while the second looks into existing works on flash smelting and Outokumpu's metallurgical research.

3.2 Post-war Finland and the war reparations to the Soviet Union

The Second World War left Finland a defeated country. The armistice between Finland and the Soviet Union, signed on 19th September 1944, required Finland to relinquish forever the Finnish Karelia, including Viipuri, the fourth largest city of Finland prior to the war, drive out the German troops still in Finnish Lapland, and pay compensations for the "damages caused" to the Soviet Union. The compensations, or war reparations, were to be mostly in form of manufactured goods and equipment worth 300 million in 1938 US gold dollars, and they were to be delivered within six years (Rautkallio, 2014, p. 7). These demands, exceeding in relative terms those demanded from Germany after the First World War (Michelsen, 2014, p. 189), were considerable to a small, still largely agrarian economy that had lost 12 percent of her land area, 17 percent of railroad network, 22 percent of timber supplies, 25 percent of wood processing plants, and about 40 percent of total hydropower capacity in use or under construction (Tiihonen, 2014, p. 159).

As Rautkallio notes in the introduction to a recent edited history of the war reparations period (Rautkallio, 2014), in immediate post-war Finland, practically every political and societal decision was in some way connected to the war reparations. The timely delivery of the goods was paramount: while the overt threat of Soviet occupation had perhaps vanished with the end of the war, the fear of the Soviets using any delays as pretexts for political pressure or even military occupation was certainly motivating the Finnish politicians and the industry. Even though the delivery deadline was extended by two years in 1945 and the total owed reduced to 226.5 million US dollars in 1948, the pressure to perform was considerable, and the war reparations program with its extensive government-industrial cooperation has sometimes been referred to as "Finland's Manhattan Project" (Michelsen, 2014, p. 199). In fact, the story of how plucky Finns defeated the obstacles, such as lack of materials, energy, and know-how, was later enshrined as a national success story (partly motivated by Cold War appeasement policy towards the Soviet Union) and was even credited as the root cause of Finland's industrialization and post-war prosperity (Wahlroos, 2014).

Recent years have seen a resurgence of interest in the history of the war reparations period, including criticism towards the Cold War hagiographies. So far, the most thorough re-examination has been performed in an edited volume of research, *Suomen sotakorvaukset 1944-1952* ("Finland's War Reparations 1944-1952", Rautkallio, 2014). The book, containing articles by leading Finnish (and one Russian) historians, a critical re-examination of the "myths" of the war reparations, and reminiscences of an industrialist who as a young engineer was involved in the war reparations deliveries, sprang from a seminar organized jointly between the Finnish cabinet and the University of Helsinki in 2012 (Rautkallio, 2014, p. 7). The volume's contributions provide insights into the background for the war reparations demands, discuss the historiography and the place of war reparations period in the Finnish national mythology, and outline the structure and some details of how the war reparations were actually delivered. The picture painted by this collection is a nuanced one, concluding that the supposed benefits of the war reparations in kick-starting the Finnish metals industry were mostly rhetorical products of the Cold War, and that Finland was certainly left poorer than without the reparations. However, the war reparations did pave way for the later, profitable bilateral trade with the Soviet Union. The emergency also motivated the industry “to do its part” in wave of nationalistic sentiment not unlike wartime, as Matomäki recalls the contemporary atmosphere (Matomäki, 2014). On the other hand, the somewhat artificial focus on heavy industry and industrial goods set during the time influenced Finland’s economic policies for decades afterwards, not necessarily in a positive direction.

The effects of war reparations in the Finnish industry have been examined in more detail in at least three recent studies. The reminiscences of Matomäki (Matomäki, 2014), published in the aforementioned edited volume, discuss the impacts of the war reparation deliveries in the machine-building industry, drawing from his experiences as a young engineer in Rosenlew, Wärtsilä and Rauma-Repola works. The same book also contained a more detailed study of Finnish shipbuilding industry during the period (Jensen-Eriksen, 2014). In another study, Joukio (2016) examined how the war reparations period influenced the Pori machine works of the Rosenlew company. Joukio concludes that the demands of the reparations accelerated the modernization of the plant, the designs, and the working methods, and thus led to permanent improvements. The period is also mentioned, at least in passing, in practically every industrial history that covers the period (e.g. Kuisma, 1985; Särkikoski, 1999; Kuisma, 2016). However, detailed works specifically examining the period and focusing on individual firms are still rare.

Nevertheless, other recent studies have examined the war reparations and reconstruction period on a more general level. Of the more notable works, Seppinen (2008) studied Finland’s “survival strategy” between 1944 and 1950, shedding light to but not definitively answering a long-controversial question: how acute was the danger of communist takeover or Soviet occupation in post-war Finland? For the purposes of this study, Seppinen’s detailed examination of Finland’s energy supply and energy strategy was most valuable addition to earlier accounts of the post-war energy crisis (e.g. Frilund, 1961). Seppinen shows conclusively that while Finland’s coal reserves were critically low during late 1944 and early 1945, the industry’s energy problems in particular began to abate after Finland joined the European Coal Organization (ECO) in April 1946. Prior to that, the most acute shortage had been relieved by Soviet deliveries as well. While the energy shortage was therefore very real, its worst impacts were short-lived.

In a similar vein but focusing on the politics and daily life in post-war Finland, Kallioniemi (2009) and Holmila and Mikkonen (2015) have mapped the mental landscapes of the period. Kallioniemi's book is aimed more towards popular audience, while Holmila and Mikkonen focus on the years 1944-49. Both of these books, however, provide a good glimpse into this turbulent period, and while they are not explicitly cited in the essays, they provided valuable background material. Other recent contributions to the history of this era include Malinen's study of housing scarcity and housing policy in post-war Helsinki (Malinen, 2014), and a study based on oral histories of demobilized war veterans by Uino (2014).

3.3 The histories of flash smelting

Flash smelting refers to a technology for smelting copper and other ores by utilizing the latent energy of the sulfide-bearing ores themselves, in addition to or instead of external energy sources. The technology was developed almost simultaneously by Outokumpu in Finland and by Inco in Canada, with the former starting up a commercial-scale furnace in 1949 and the latter in 1952. However, the two companies approached the problem somewhat differently, and their furnace designs were quite different, even though the basic principle was the same. The development and history of this technology forms the core of the main case study of this thesis, and a brief history of its history is therefore in order.

Given the importance of flash smelting as a radically energy-efficient way to smelt copper and, later, other ores, its relative absence from the annals of technology is somewhat surprising. However, the same can be said of most other metallurgical inventions. With few exceptions, these technologies are confined to the pages of specialist metallurgy journals and textbooks, and their histories are often discussed only in passing.

In this manner, the earliest histories of flash smelting were contained in the lectures and articles introducing the technology to other metallurgists. The first existing example of such "potted" histories can be found in the lecture given by one of the inventors of the technology, Outokumpu's chief metallurgist and later managing director Petri Bryk in 1949.[1] Speaking in an event organized by the Finnish association of mining engineers (*Vuorimiesyhdistys*), Bryk touched briefly the origins of flash smelting in the earlier "pyritic" smelting process, which had utilized the latent heat of sulphides as well, but fell into disuse as the peculiar deposits of copper ore it required had been exhausted by 1930s. Essentially the same lecture was published in 1952 in a specialty magazine published by the German supplier of fireproof furnace bricks to Outokumpu (Bryk, 1952). Flash smelting was also mentioned in an article penned by Outokumpu's managing director Eero Mäkinen for a "Special Survey of Finland" published in the English newspaper Continental Daily Mail in December 1949 (Mäkinen, 1949).

Later accounts reiterated these roots and added more detail regarding the experiments that led to the development of "proper" flash smelting. In 1955, the prestigious *Journal of Metals* published an article written by "Staff of Inco", detailing the company's new flash furnace design and its development (Staff of Inco Mining and Smelting Division, 1955). The article noted that the roots of the technology could be found in the patents and experiments conducted in around 1897 by H. L. Bridgman in the United States (Bridgman, 1897), and traced the developments through later patents (Klepinger et al., 1915), experiments and research (e.g. Cooper and Laist, 1933; Freeman, 1932). A similar brief historical overview was also given in later article to the same journal by Bryk et al. (Bryk et al., 1958). Given that the latter article provided even more historical detail and connected Outokumpu's furnace to work conducted before the Second World War in Jugoslavia and even the Soviet Union, it is interesting to note that the article did not mention the early 1930s experiments by Cooper and Laist (Cooper and Laist, 1933), even though — or parhaps because? — the earlier Inco article noted that Outokumpu's furnace bore a close resemblance to Cooper and Laist's experimental furnace.

With the exception of brief chapters on the development of flash smelting in the two histories of Outokumpu the company commissioned (Annala, 1960; Kuisma, 1985), similar sporadic overviews in lectures, articles and textbooks (of an example of the latter, see e.g. Biswas and Davenport, 1976) were the extent to which the technology's history was discussed until 1990s. In two articles published in the metallurgy journal *CIM Bulletin*, Habashi discussed specifically the history of Outokumpu's flash smelting (Habashi, 1993, 1998). At the same time, the principal developer of flash smelting at Inco,

[1] Liekkisulatus Harjavallassa. Esitelmä 27.3.49 Vuorimiesyhdistyksessä. Dipl. ins. Petri Bryk. Outokumpu archives at ELKA, Toimitusjohtajan huonearkisto, folder Autogen etc.

Queneau, authored an article detailing the development of Inco's version of the technology (Queneau and Marcuson, 1996). Finally, the approaching fiftieth anniversary of the invention led directly to the commission of a special history of the Outokumpu flash furnace (Särkikoski, 1999). Published in 1999, it remains the definitive study of Outokumpu's efforts to develop a flash furnace, and alongside the history of Outokumpu's metallurgical research published in the same year (Mäntymäki, 1999), it formed one of the main sources for this thesis. During this millennium, the same basic story of the "metallurgical invention of the century" has been retold in various articles (Kojo et al., 2000; Moskalyk and Alfantazi, 2003; King, 2007), lectures (Taskinen, 2009), and in Nykänen's history of Outotec, the former technology division of Outokumpu (Nykänen, 2016).

A trend visible in these histories is that Outokumpu managed to influence the narrative of its great invention to a considerable degree. From the earliest lectures onwards, the technology was presented as a direct, sometimes even miraculous response to the post-war energy crisis in Finland. For just one example, in the 1949 newspaper article Eero Mäkinen discussed flash smelting in no uncertain terms:

> "In jest, it can be said that this invention consists of 'a third of an atom bomb, a third of perpetuum mobile and a third of Columbus' egg."' (Mäkinen, 1949)

The wondrous status of the technology is evident from this and many other passages aimed at public consumption. Unfortunately, as far as I'm aware, there are no histories of Inco's development of flash furnace that even remotely match the detail provided by Särkikoski (1999), and what archives remain from this once-proud company have been closed to researchers. It is therefore hard to say whether similar sentiments were shared by Outokumpu's Canadian rivals, and what they thought — if anything — about the fact that Outokumpu's furnaces provided at one point 60 percent of world's primary copper (Moskalyk and Alfantazi, 2003), while their technologically superior furnace remained Inco's sole property until 1970s. If the Inco archives become accessible at some point in the future, examining the Inco point of view in more detail would be an interesting research project.

Chapter 4

Essay I: The stories we weave

Narrative bias in historical case studies in management, organizational and innovation studies

4.1 Introduction

Case studies play an irreplaceable role in the study of management, organizations, innovations and innovation management. Without their qualitative, longitudinal narratives, our understanding of past events would be limited to incomprehensible, disjointed factoids. However, the use of narratively styled histories presents a problem that this paper suggests is underappreciated in the innovation studies: the conscious and unconscious reworking of historical events to fit a human bias for a smooth narrative that supports a definite, perhaps even exaggerated conclusion.

In the past, numerous scholars in different fields of study have noted that even non-fictional and scholarly narrative accounts are often subtly crafted to conform what the narrator thinks forms a "good story" (e.g. White, 1973; Landau, 1984; Roeh, 1989; Landau, 1993; Young and Saver, 2001; Manning et al., 2007; Edgerton, 2006; White, 2010; Lewis, 2011). This tendency should not be surprising: humans have a known tendency to think through narratives and subtly distort or even force their observations to fit into a preconceived format (Young and Saver, 2001; Manning et al., 2007; Taleb, 2007). From birth, most humans are bombarded with narratives, and schools and universities even offer courses on storytelling and how to craft scholarly research into a catchy narrative. Furthermore, ideological and other preconceived notions influence greatly the stories we tell. As critics have shown, scientists and scholars are nevertheless often unaware of the extent to which they are actually using narrative in their thinking and in communicating their ideas (Landau, 1984). Given that scholars of literature, cognitive scientists and even historians have for long argued that storytelling is what actually makes us human (Huxley, 1963; Harari, 2014; Kearney, 2002), this should not be surprising: we should be more surprised if storytelling *wasn't* so widespread.

The questions these insights pose in the context of management, organization and innovation studies are obvious: to what extent are our historical narratives, including case studies, "contaminated" by a narrative bias? Does narrative bias result to exaggerated conclusions — either overly optimistic or overly pessimistic? Is narrative bias a problem, or just a feature of case study methodology? And if it is a problem, what could or should be done about it?

The questions posed here are not new. Historians have discussed similar issues at least since White's seminal *Metahistory* (1973), and postmodern scholarship in particular has repeatedly claimed that much of science is actually comprised of competing narratives (e.g. Lyotard, 1984). However, even though there are several fine methodological works aimed at researchers wishing to *analyze* narratives (e.g. Gubrium and Holstein, 2009; Holstein and Gubrium, 2012), the potential problem of fitting facts into a preconceived narrative has merited little discussion in methodology texts familiar to most innovation, management and organizational scholars (e.g. Eisenhardt, 1989; Gerring, 2007; Flyvbjerg, 2006; Yin, 2013). I therefore believe it is worthwhile to occasionally remind new scholars — particularly those who, like myself, come from fields like science or engineering where critical literature studies aren't part of the curriculum — about how the stories we tell are influenced by what we *want* to tell, and how even the most apolitical story may carry unintended ideological implications. This is a necessary discussion to have in view of the ongoing historical turn in management and organization studies (Maclean et al., 2015; Rowlinson et al., 2014b; Rowlinson and Hassard, 2013; Clark and Rowlinson, 2004). As management, organizational and innovation scholars are increasingly using historical methods and historical case studies (for some examples in innovation studies, see Gibbert and Scranton, 2009; Korhonen and Välikangas, 2014), we can all benefit from examining past debates in historiography.

While the focus of this paper is on the use of historical cases in innovation studies, I trust the message is universal and valuable to researchers using other methods and working in other disciplines. Even when we're working with strictly quantitative material, we have the same human tendency to tell stories, and suffer from similar biases. However, in order to avoid any misunderstandings, I wish to emphasize that this paper does *not* argue that research is just storytelling, that facts don't matter, or that all stories are equivalent or equally suspect. Even the doyen of narrative critique Hayden White (1973) and his commentators (e.g. Doran, 2010) rightly maintain that the fact that historical accounts are stories does *not* in any way legitimize bad research or spurious relativism: any study can and should be assessed according to the truth value of its factual statements and the logical conjunction of the whole.

This paper investigates the presence of narrative bias through a re-examination of two case studies of human ingenuity in face of constraints, namely a study of creativity under pressure during failed Apollo 13 moon mission (King, 1997) and an examination of early jet engine history (Gibbert et al., 2007; Gibbert and Scranton, 2009; Schubert, 2004). I shall supplement the case narratives with some additional details in an attempt to show that we could construct very different narratives, to argue for very different conclusions, from the same data — just as White (1973) noted years ago. In particular, I will focus on the tendency of research to promote optimistic conclusions, although the same mechanism seems responsible for the promotion of overly pessimistic conclusions as well.

These two studies are featured in this paper due to my previous work on the question of resource scarcities and constraints, which led me to familiarize myself with primary sources relevant to these studies. Both cases have been cited in existing scarcity/constraints and emerging ingenuity stream (recently by e.g. Weiss et al., 2011; Hoegl et al., 2010; Weiss et al., 2013, 2014; Lampel et al., 2014; Honig et al., 2014), and a retelling of these cases could therefore serve the emerging ingenuity research community. Furthermore, by using cases from engineering history, I hope to make a point: if narratives and stories can be constructed so easily in a field that's supposed to be at least delimited by hard facts, how easy it may be in fields where there are even fewer solid facts to anchor the stories into? However, practically any case study could have served as an example and nothing in the present paper should be construed as an attempt to denigrate the commendable scholarly work immediately apparent in the aforementioned articles. I did not choose to use these case studies because I thought they were deficient, but because

I think they are examples of *good*, inspired scholarship.

The paper is organized as follows: first, I shall present the argument for understanding research as a form of storytelling. Second, I review some of the pertinent literature on narratives and what, following Taleb (2007) I call *narrative bias* in case studies. I will also introduce my reasoning why arguments in scholarly studies tend to bifurcate towards optimistic or pessimistic conclusions. After this theoretical review, I briefly outline the narratives of the two case studies in question, and continue with a discussion of how historical facts could yield a completely different interpretation. Finally, I conclude this paper with a discussion how narrative bias may lead researchers to either too positive or too negative conclusions, and offer some suggestions about how these narrative biases could and should be dealt with in research and teaching.

4.2 Research as storytelling

As Misia Landau noted in her classic study of narratives in evolutionary biology, any set of events that can be arranged in a sequence and related can also be narrated (Landau, 1993, 1984). Generally speaking, case studies are a form of storytelling where we construct a story from a historical set of events, for the purposes of advancing a specific argument. It matters little *how* exactly we construct the case study: with the exception of purely chronological lists of events ("chronicles"), *all* case studies are narratives of one sort or another. Case studies and other stories are not "found". they are created, and the "facts" do not dictate the form of the story. This is a point argued persuasively by eminent theorist of historical writing Hayden White, who believed the distinction between narrative and non-narrative histories is generally meaningless (White, 1973, 2010).

In *Metahistory*, his *magnum opus*, White (1973) illustrated how even histories we generally don't think of as narratives in fact can be fruitfully understood as such. White's insight was to realize that even histories we don't always recognize as narratives are in fact exemplars of *different* narratives. Even works that seem to have no story, no plot, no beginning nor end, or hardly even an argument can be thought of as a stories that follow what White calls "Ironic" plot-structure: "stories that go nowhere precisely because they are intended to frustrate expectations that there is anywhere to go" (White, 2010, p. 117). However, most case studies tend to follow more traditional narrative conventions.

These stories we tell are by necessity simplifications. We can never tell the "full story" with all the details for the same reason there are no maps with a scale 1 to 1: reality is the only "full story" there is, and all attempts to condense it necessarily abstract out some detail. When we write our case studies for scholarly journals, the page limit alone forces us to be extremely selective and to focus on the aspects we believe best advances the argument we wish to advance. We cannot avoid such selectivity even though scholarly writing attempts to provide nuance and we usually try to mention, at least in the footnotes, the weak spots in our arguments. After all, centuries of scholarly tradition have stressed that our task in writing a scholarly paper is to provide the most convincing argument possible.

None of this implies we researchers are dishonest or engaging in bad research practice. On the contrary, all the methodology texts I've read emphasize that selectivity is at the core of good case study research, from data collection to presentation of findings (for prominently cited examples, see Eisenhardt, 1989; Gerring, 2007; Flyvbjerg, 2006; Yin, 2013). This is only necessary for the stories we tend to tell, that is, stories whose primary purpose is to "illuminate and carry on an argument" (White, 2010, p. 125). Otherwise, we couldn't find readers for our overly long stories, nor could we publish them in scholarly journals. After all, even monographs are far too short for a complete treatment of all but the simplest of topics.

But because stories we tell must be simplifications, what matters a great deal is what we decide to leave out — and how we make these decisions. Even if equipped with the same set of objective facts, two researchers with different philosophies, interests or approaches can come up with quite different narratives arguing for very different things, as White originally pointed out. A pessimistic (often a conservative) scholar tends to interpret the historical events as a support for pessimistic conclusions, while an optimist (often a radical) tends to see silver linings in every cloud.

In short, the facts, even when objective truths, do not dictate the form of the story: instead, the researcher must necessarily reconfigure the simple chronicles in a process that can only be described as fundamentally aesthetic or even poetic. When we have facts in abundance and can pick and choose the ones that best fit the argument we intend to make, the problem is only exacerbated.

4.2.1 Narrative bias

Crafting a good presentation of a case study, or any sort of research narrative, is a skill requiring fine judgment; in other words, an art.

The writer must be able to first whet the interest of the reader and then keep her interested throughout, while presenting a convincing argument that makes a significant contribution in what is hopefully an authoritative manner. As researchers, we are repeatedly encouraged to pursue research whose results can make a significant impact and "be as bold as our capabilities and resources allow" (quoted in Huff, 2009, p. 29). At stake is not only our influence in the scholarly community, but also our future as scholars: without impactful publications and research results, our careers are likely to be cut short.

A disinterested observer would be perfectly justified in assuming that these career pressures alone, and particularly in combination of trying our utmost to be convincing, are likely to result in various biases in our work. Perhaps the most insidious of these biases is what is called *narrative bias* or narrative fallacy (after Taleb, 2007): our innate preference for compacted stories that follow specific narrative formats over messy, ambiguous raw data.

As mentioned in the previous section, we humans are storytelling creatures. Some psychologists and cognitive scientists even argue that our cognitive capabilities actually shut down in absence of a story (Dawes, 1999; Young and Saver, 2001). As a result, we try to extract a story from almost any set of observations. For example, imagine a picture depicting a frowning adult, a child with a lasso and a cowboy hat, a cat, and a shattered vase on the floor, next to a cupboard.

What has happened? Many if not most humans would readily suggest that the child has been playing and knocked down the vase. In other words, we invent a story with a beginning (a playful child), a middle (an attempt with a lasso) and an end (the shattered vase) that describes what has happened. These stories we invent tend to be simplifications. We might ignore the role the cat or the adult might have played, for example, and we often jump to conclusions we find most plausible. Often, what is most plausible and what makes the "best" story are the same things. In other words, we think a good story must, among other features, also be plausible — and, in return, a good story seems more plausible to us.

As Dan and Chip Heath put it in their popular book *Made to Stick* (2007), ideas that "stick" to people's minds tend to be delivered through simple, somewhat unexpected, yet concrete and credible *stories*. The two could have been describing what makes a good scholarly case study. These, too, try to make the idea or argument contained within to stick in the minds of its readers. Consciously and unconsciously, we craft the facts at our disposal to form an accepted sort of narrative, a recognizable story where there (usually) is a beginning, a middle, and the end; often, a protagonist and a challenge she needs to overcome; and, in impactful scholarly studies, an unexpected claim that in some way goes against the accepted wisdom and "constitutes an attack on the taken-for-granted world of their audience" (Davis, 1971, p. 311; see also Huff, 2009). It is worth noting, however, that there's no requirement whatsoever for the effective and interesting story to be actually *true*: what's only needed is that the story is credible. Even the most outrageous lies can be spread through "sticky", technically brilliant stories.

Taken together, our tendency to construct stories, our susceptibility to and desire for good stories, and the need for condensed, readable accounts that make an argument (particularly for work published in scholarly journals) can produce the narrative bias mentioned above. In our desire to tell an engaging and a convincing story while simultaneously pressured by the word count, we may well leave out details that simply don't fit into the narrative we're thinking about — or do not support the argument we're trying to make. Sometimes these omissions are certainly justified, as not all details matter equally. But our brains are extremely adept in tricking us into thinking what we believe is also what is correct, and our judgments are famously suspect.

4.2.2 Argument bifurcation

It seems that the aforementioned combination of our tendency to construct stories, our susceptibility to good stories, and the need for condensed accounts that make a point tend to manifest in two very popular story archetypes in research literature and popular discourse: the optimistic and the pessimistic. Researchers who are philosophically or otherwise inclined to see the world optimistically may be also inclined to interpret past events in an optimistic light, producing case studies like the two examples above. After all, success after adversity is the archetype of optimistic story. Those who agree with the optimistic view of the world (including journal editors and reviewers; Bushman and Wells, 2001 found that reviewers can be biased by an interesting *title*) are likely to nod their approval, as the story confirms their preconceptions. On the other hand, another immensely popular format is the pessimistic story, where humans struggle to no avail. This archetype, too, has its proponents, and much of the environmental literature in particular could serve as examples.

It is easy to hypothesize a potential mechanism that produces such bifurcation. When arguing for a position, be it optimistic or pessimistic, one is likely to use the best arguments possible and minimize anything that could detract from the argument. The opponent, however, is likely to respond likewise — but with the opposing interpretation, of course. After a few rounds of this back and forth, middle of the road arguments simply don't have a point any longer. "Ambidextrous" (on one hand... on the other) results that confirm *both* sides of the argument aren't likely to lead to publications, except when they can be interpreted (again, interpretation) as reconciling previously opposing viewpoints (see Huff, 2009). Ironically, however, successful reconciliation again requires convincing others with a captivating *story*, with the similar potential for cutting corners or smoothing out irregularities.

In the next sections, I shall look into two well-executed case studies and show how the facts can be used to tell very different stories, depending on what particulars are highlighted and what wrinkles are smoothed over.

4.3 Apollo 13 and ingenuity under pressure

Does necessity beget creativity and innovation? According to my first example, a study by Margaret J. King, the answer is yes, and the ill-fated Apollo 13 moon mission serves as a dramatic example of "the grace under pressure that is the condition of optimal creativity" (King, 1997, p. 299). King argues that some of the best creative problem solving happens under extreme conditions, as demonstrated by the numerous jury-rigged solutions the mission control and the crew of crippled Apollo 13 spaceship had to invent and implement. At stake was not only the lives of the three astronauts, but the standing, credibility and the very idea of the United States of America: "a lifetime of staring skyward at the orbiting tomb of an Apollo traveling in an eternal and hopeless journey, *an American dream gone terribly wrong on view of the whole planet*" (p. 302, emphasis added).

Writing in 1997, two years after the release of blockbuster Tom Hanks film *Apollo 13*, King assumes the readers are familiar with the outline of the story presented in the film: how an explosion in the spacecraft crippled its life-support systems and how the heroic efforts of the ground crew and the astronauts saved the day and turned a potential disaster into one of NASA's finest hours. Building on this cinematic premise of astronauts in peril in their makeshift lifeboat née Lunar Module, King recounts displays of ingenuity such as juryrigging square-shaped Command Module carbon dioxide scrubbers to fit round-shaped Lunar Module receptables in order to prevent CO_2 buildup to dangerous levels, or the use of Earth as a navigational aid for a course correction maneuver.

By focusing on these examples, King argues that after the mission "went off course," the astronauts (and, by extension, the American dream) were saved not by meticulous planning and forethought, but by creativity humans show under pressure.

> "The six-month planning and practice for the flight provided rehearsal. But this preparation proved to be only indirect training for the untoward events that developed. Under the confines of the new 'box', new ways of thinking were not logically anticipated, nor chosen, but imposed. It was a whole-brain exercise drawn from expertise developed over a lifetime, out of which novel solutions were forged." (p. 302)

Throughout her case study, King presses the argument that creativity can and does flourish under pressure, and that lessons learned can be applied to businesses, research, and even relationships. If only we are not allowed to quit — when "failure is not an option" — we can turn adversity into innovation and thus snatch victory from the jaws of defeat. Extraordinary circumstances, King argues, "provoke creative action" that "galvanized the spirited, perhaps even spiritual response of people for whom acting and thinking had become the same thing: heroic action translated into audacity of mind" (p. 307). In the end, innovations are catalysed once "the American cultural values" are mobilized to the problem-solving process.

The Apollo 13 case and, in particular, the movie indeed present an inspiring story about creativity and the value of coolness under adversity. This is because the movie tells a gripping story, as blockbuster films often do: one might not go too far out on a limb by arguing that *this is what movie-makers try to do.* However, the movie (and the autobiographical book the movie is based upon, Lovell and Kluger (1995)) are stories, and as argued above, they necessarily leave out certain details — in addition to the movie taking certain dramatic liberties, some of which (such as the exaggeration of the role played by a grounded astronaut) have carried into King's case study.

Other available sources, such as official NASA reports (Cortright, 1970; NASA/MSC, 1970), other case studies (Goodman, 2009) and the memoirs of Flight Director Gene Kranz (Kranz, 2000) could be used to craft a quite different story with very different lessons. Instead of the optimistic message of necessity being the mother of invention, one could also use the *same event* to argue that ingenuity doesn't thrive under pressure but results from hard work and long preparation, and that luck of the draw matters more than any values or approaches. This would be almost the exact opposite of the argument King is making.

Consider, for example, what the introduction to the official Mission Operations Report (NASA/MSC, 1970) states, matter-of-factly:

> "[...] the procedures used in recovering from the anomaly were, in a great many instances, *fairly well thought out premission*" (p. I-1, emphasis added).

Beginning from this introduction, these other sources paint a picture where the planning and preparation for the mission — and no small amount of luck — played a crucial role in returning the astronauts safely to Earth. The only innovation that was deemed worthy of special acclaim in the official reports was the development and verification of new atmospheric re-entry procedures due to unusual spacecraft configuration (Cortright, 1970, p. 3-29), a feat that is indirectly featured but not actually discussed in the 1995 film (although it is mentioned in the book the film is based upon). While the jury-rigged CO_2 scrubbers are a major plot point in the film, the ground crew was actually more concerned about water, necessary for cooling the onboard electrical systems. If the scrubbers couldn't have been jury-rigged as shown in the movie, at least two other options were available. Post-flight analysis determined one of them might have been preferable to the jury-rigged system actually used (NASA/MSC, 1970, p. E-11).

However, in the end all these problems were overcome through hard-won expertise, acquired through hours and hours of rehearsals and practice and consideration of dozens of different "what if" scenarios. While no scenario had simulated precisely the series of events that actually occurred, there is little doubt that pre-flight preparations, taken together, were what really enabled the team to come up with necessary fixes and solutions to this particular emergency. As the final report of the Apollo 13 review board curtly states (Cortright, 1970, p. 5-33, emphasis added),

> "*Earlier contingency plans and available checklists* were adequate to extent life support capability of the LM [Lunar Module] well beyond its normal intended capability."

In fact, being creative under pressure comes attached with its own problems. A 2009 analysis of the Apollo 13 mission sternly warns future mission crews that the high-pressure environment of a time-critical spacecraft emergency makes it easy to make mistakes when using analysis tools, developing novel procedures, and performing tasks (Goodman, 2009, p. 32). As an example, the study shows how an error in a hastily developed maneuver procedure — confusing two directions — nearly resulted to possibly unrecoverable (that is, fatal) condition known as "gimbal lock." While the study readily acknowledges that not every contingency can be foreseen and existing plans may need extensive modifications, it stresses the importance of pre-flight training and familiarization as critical enablers of successful crisis management: "Successful recovery of the Apollo 13 crew was facilitated by pre-mission development of contingency procedures" (Goodman, 2009, p. 33).

Finally, one has to ask how different stories we might tell had just a few things gone differently. Without detracting anything from the creative performance exhibited by the Apollo 13 mission crew, the truth is that luck was quite possibly the greatest single factor facilitating safe return of the astronauts. During the whole ordeal, the elephant lurking in the control room and aboard the stricken spacecraft was the condition of the craft's heat shield (see e.g. Kranz, 2000; Lovell and Kluger, 1995). If, as many feared, it had been cracked in the violent explosion or its aftermath, even the most heroic efforts imaginable couldn't have prevented the crew meeting their ends during their fiery plunge to Earth's atmosphere. The risk was real, but there was absolutely nothing anyone could do about it; therefore, the mission crew deliberately avoided even discussing the possible damage, just as they avoided discussions of other potentially fatal problems they couldn't hope to solve (Kranz, 2000, p. 334). Would we hear stirring tales of ingeniously jury-rigged CO_2 scrubbers if the mission had ended in an expanding fireball high above the Pacific?

4.4 Nickel shortage and jet engines

The second example case looks at how a shortage of raw materials might benefit innovation. In brief, at least three relatively recent studies (Schubert, 2004; Gibbert et al., 2007; Gibbert and Scranton, 2009) have claimed that a shortage of nickel, a key component in heat-resisting metal alloys, caused wartime German jet engine designers to invent a radically novel technology that enabled them to bypass the lack of suitable alloys. Furthermore, these studies imply that the invention — air-cooling the most affected parts — was later adopted in all jet engines, and therefore the shortage accelerated the development of jet engine technology. In two management studies articles (Gibbert et al., 2007; Gibbert and Scranton, 2009) and in several publications citing these papers (e.g. Weiss et al., 2013; Lampel et al., 2014; Banerjee, 2014; Korhonen and Välikangas, 2014; Scopelliti et al., 2014), the jet engine story is used, alongside other case studies, to argue that constraints can spur ingenuity and innovation.

As with the Apollo case above, there is nothing *wrong* per se in this narrative. However, the historical events could also be interpreted to suggest that the causality didn't run from constraints to innovation but from invention to constraints, and that the invention itself was both obvious and somewhat of a dead end that did not meaningfully impact jet engine development in general.

To explain why, it is necessary to explain briefly how early jet engines (turbojets) worked. A turbojet engine operates by burning fuel in a compressed air and using the released energy both to drive the compressor and propel the aircraft. A shaft running through the engine attaches the compressor to a turbine. Turbine takes on the full blast of superheated gas from the engine's combustion chamber and has to convert part of the gas's energy into rotary motion, used by the compressor to push more air into the combustion chamber.

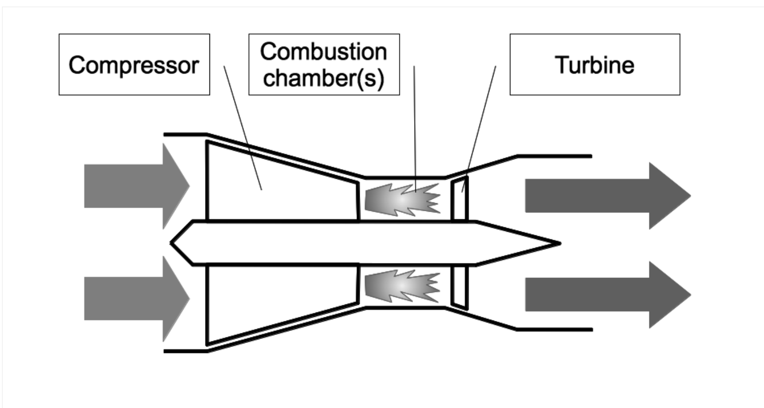

Figure 4.1: Schematic of a jet engine.

As a consequence, the requirements for the turbine are formidable: not only it has to spin at an astounding speed, imparting severe centripetal stress to its parts, but it also has to do so while enduring extremely high temperatures. This combination would cause most metals and alloys to strain and break in a phenomenon known as creep. Furthermore, the efficiency of a jet engine is directly proportional to the highest temperature it can safely tolerate: higher temperature means more power and better fuel economy.

The problem facing the German jet engine developers was that suitable high-temperature alloys required nickel. This metal was required for all sorts of militarily important alloys but was scarce in Germany, in contrast to the Allies, who enjoyed an abundant supply. The nickel shortage had been acknowledged even before the war (Perkins, 1992), and the German research establishment had experimented with concepts that would reduce nickel demands in manufacturing. A research that had direct bearing to jet engines was research on piston engine power boosting using turbo-superchargers, which are in effect small jet engines powered by the exhaust of a piston engine, and likewise demand heat-resistant alloys. First really practical alloys for such applications appeared in the early 1930s (**?**), but in engineering, an obvious alternative to more heat-resistant materials is always a cooling system. Due to this lack of suitable alloys (and *not* because lack of nickel), German turbocharger researchers had tested air-cooled turbocharger turbines already in 1929, and by 1938, engine manufacturer BMW had such an engine in production (Anonymous, 1938; Schubert, 2004). When BMW started to develop jet engines in 1938, its successful air-cooled turbocharger was a natural starting point, particularly since many future jet engineers had experience with them (Gunston, 2006; Schubert, 2004; Kay, 2002).

Therefore, when the German economy began to gear up for war following the Nazi rise to power in 1933, the concerns of nickel availability coincided with a technology that could in part reduce demand for nickel. Air-cooled turbines could be manufactured using less nickel than uncooled turbines, and jet engines in general would use less nickel than existing piston engines (Kay, 2002). Against this background, it is not very surprising that the German air ministry encouraged the researchers to develop air cooling for jet turbines as well. This they did, and once considerable development and manufacturing challenges were surmounted, air-cooled turbines went into production in late 1944 (Kay, 2002). However, before these parts reached combat units, the war was already over. The German jet fighters that flew in combat used turbines made from uncooled high temperature alloys, just as their counterparts in Britain. Nickel constraint did not prevent or even slow down the deployment of uncooled turbines.

In fact, the nickel constraint could be argued to have been *caused*, at least in part, by the availability of a technology (air-cooled turbines) that required less nickel. Jet engines constituted only a very small portion of Germany's nickel demand: despite using uncooled turbines for the most part, the entire production run of the most important of two engine types, Jumo 004, required only about 40 metric tons of nickel in total (calculated from Kay, 2002). Equivalent amount of nickel would be spent on the armor plating of only 27 heavy Tiger I tanks, of which alone about 1350 were produced, alongside thousands of other armored vehicles and other weapons also reliant on nickel (Jentz et al., 1993). Furthermore, even "uncooled" jet engines used less than half of the nickel required for even somewhat comparable piston engines, while providing a great increase in performance (Gregor, 1998). Finally, post-war research has concluded that Germany actually managed to increase its nickel reserves during the war (Norcross et al., 1947; Vuorisjärvi, 1989). The issue, therefore, was not availability of nickel but its allocation by the German authorities. In this light, another plausible explanation for the nickel constraint in jet engine development is that it remained a constraint because of a promising technology that undermined the pressures to relax the constraint.

But what of the argument that this constraint, whether it was real or merely perceived, nevertheless prodded German designers to come up with a valuable innovation that was adopted by others after the war? Unfortunately, this narrative can also be questioned. As mentioned above, cooling is an obvious engineering solution to any situation where heat resistant materials alone aren't enough. However, nothing in engineering comes without tradeoffs: in the case of turbine cooling, the cooling air needs to come from somewhere, and this means a decrease in overall engine performance. Together with a turbine manufacturing method that optimized production at expense of aerodynamic efficiency, the performance penalty could have been as much as 10 percent compared to an uncooled turbine (according to British evaluation, Kay, 2002). This is a significant penalty for military jets and, in combination with other issues introduced by cooling, goes a long way towards explaining why the British jet engine designers did not choose air-cooled turbines and why their evaluations of German jet engines were quite dismissive (see e.g. Staff of Power Jets, 1945, also Giffard, 2016 for manufacturability). In fact, even German designers abandoned the concept in their post-war work for the French aircraft industry (von Gersdorff, 2004).

Because cooling was such an obvious solution, it is an overstatement to say the Germans "invented" it due to the nickel constraint.

The British had in fact tested conceptually similar designs independently in 1942 (Eyre, 2005), but performance and other penalties cooled (as it were) their interest. Only after the limits of high-temperature, high-nickel alloys were reached in the 1950s, did air cooling make a comeback. But it did it in a form that owes very little to German wartime efforts: while the German solution had been to construct hollow, internally cooled turbine blades from thin sheet metal, the demands of the 1950s precluded such crude, inefficient designs. Instead, all post-war turbine cooling systems have used a design essentially similar to the one the British already tested in 1942, where otherwise solid turbine blade is manufactured with thin internal cooling channels (Gunston, 2006). These would have been invented with or without German work.

Figure 4.2: German and modern turbine air cooling.
Evolution from thin-walled sheet metal to solid with cooling channels.

4.5 Discussion: narrative bias in O & M case studies

The two examples above show one form of narrative bias in action. They both have a group of protagonists who, more or less unexpectedly, have to embark on a quest of high importance: survival on one hand, winning the war on the other. The protagonists are beset by a series of challenges, which they overcome despite the odds, demonstrating wit and ingenuity under pressure. Finally, the protagonists are vindicated in the eyes of the world — space launch "as exciting as a trip to Pittsburgh" (King, 1997, p. 304) turns into a gripping drama with a happy ending and a blockbuster movie, and the tools of one of the most horrible conflicts in history lead to a technology that today helps bring the world together.

We humans desire such stories with difficulties followed by a happy ending, as demonstrated by our continuous thirst for books, movies and other story-based entertainment. We are also acclimatized to such stories from a very young age, and are likely to unconsciously value stories with such narratives and story arcs over stories without. Finally, our desire to produce impactful research practically compels us to present our findings in a format that is all but proven to be the most likely to engage the audience.

The problem is that the reality is under no obligation to follow an archetypical story format. When we craft our research narratives from available data, we therefore often have to streamline or even jiggle the events in order to make a the story work. What's more, we're biased by our desire (and, in scholarly work, requirement) to make a point. If, for example, we wish to argue that constraints are good for creativity and innovativeness, we are likely to jiggle the events so that our story supports our argument. On the other hand, if we wish to convey an opposite message, we are equally likely to construct a story that focuses on the negative and leaves out anything that does not agree with the overall thrust of our argument. As I've hopefully shown above, the events themselves usually lend credence to even exactly opposing arguments. This is true even in relatively "hard" engineering, and particularly true in the social sciences, where there is no world "as it is" because the phenomena we study are almost always constructs of the mind.

As researchers, we very often like to pretend objectivity and think that we let the data tell us whatever conclusions it may. As researchers, we also know this is simply not true. Each of us brings our own prejudices and preconceptions into research. We are condemned to see the world through the lenses we've constructed for ourselves (or someone else has constructed for us), and while we can sometimes construct new lenses, grinding them is slow work at best.

Nothing here means I'm accusing any researchers of conscious motivated reasoning (using facts to build a predetermined case rather than letting facts lead to a conclusion). Such behavior is of course common in popular discourse and while it probably occurs in the academia as well, it seems to be thankfully rare. Nevertheless, the ease with which the same set of facts can be interpreted in very different ways should be a cause of concern for anyone who is interested in finding the truth, or at least a close approximation of it.

The problems I've raised here are only too likely to be exacerbated by current pressures to produce research that makes a splash. As researchers are graded more and more on the impacts of their studies, and as interesting results are more likely to be published, the temptation to "storify" research results and leave out anything that doesn't support the argument must only increase. One possible method of assessing whether this is happening could perhaps be to analyze research articles to see whether they point out potentially ambiguous elements or counter obvious counter-arguments.

What, then, is there to be done? For a start, it might be a good idea to be more explicit about possible biases or preconceptions about the results of the study. A section about possible researcher biases could accompany the usual discussion about the choice of research methods, data sources and the justifications for inclusion or omission of specific events, sources or theories. A researcher is of course allowed to do research that confirms her preconceptions — without such hunchs, not much research could be done — but it might be useful both for the researcher and for the reader to state up front where and whether the research confirmed existing beliefs. The problem, of course, is that understanding our own biases may be difficult and at the minimum require considerable self-reflection.

It might also be useful to record the expected results before the study is even initiated. Many medical science authorities, for example, are now encouraging researchers to submit their research plans and tentative hypotheses in advance in order to prevent ex post hypotheses and p-value hacking in the pursuit of publishable results. We in the social sciences might benefit from similar arrangements as well. Publishing outlets could also think whether their demand for "interesting" research could be contributing to the narrative bias.

From the viewpoint of an individual researcher, a good reality check might be to be wary if the work in progress seems to confirm a hunch or a preconception we had when starting the study. Recording the hunch in advance, if only in a personal journal, would probably serve us well: while our hunches often turn out to be correct, history has no obligation to validate them. We ought to be alarmed if our research seems to confirm our preconceptions with any great regularity.

Finally, in teaching students and next generations of researchers, it might be useful to discuss the narrative bias with help of examples. Building two completely different stories from same research data could be a useful training exercise, particularly for those who, as mentioned in the Introduction, lack exposure to literature studies and similar disciplines from their prior education. Presenting different viewpoints that may lead to completely different conclusions would also seem to be an useful educational device that helps our students to see the world as it is, not as a clear-cut story but as a messy, uncertain and often maddeningly ambiguous bricolage continuously built and re-built by billions of humans and countless billions of other lifeforms.

Chapter 5

Essay II: Constraints and Ingenuity

The Case of Outokumpu and the Development of Flash Smelting in the Copper Industry

The extent to which constraints help or hinder ingenuity remains a matter of some debate. In particular, the relationship between resource constraints and technological innovation remains murky, and detailed case studies are rare. In this chapter, we document the invention of novel copper smelting technology after a post-war energy crisis. The particular technology is still dominant in the mining industry. It emerged as an incremental combination of previously existing technologies, independently discovered by two companies in Finland and Canada at about the same time yet anticipated decades before its first use. We conclude, based on the study, that constraints make innovators (people who engage in ingenuity) more likely than novel innovations (new technologies require a longer incubation period than resource constraints generally allow).[1]

5.1 Introduction

Prior work on ingenuity under constraints has focused on whether resource constraints and operating limitations help or hinder creativity, innovation, and organizational performance. Although the

[1]This article, co-authored with Liisa Välikangas, has been published as a part of *Handbook of Research on Organizational Ingenuity and Creative Institutional Entrepreneurship*, edited by B. Honig, J. Lampel and I. Drori, Edward Elgar, 2014, pp. 254-276. Reproduced here with permission. The author provided the basic idea, analysis, and most of the writing; Liisa Välikangas helped improve the idea, revise the draft, and sharpen the analysis.

evidence is somewhat inconclusive, as discussed below, an emerging consensus seems to be that constraints may trigger cognitive and organizational mechanisms that promote creativity, innovativeness and other desirable characteristics. However, what is missing in most prior studies is a detailed "autopsy" of constraint-induced fruits of ingenuity, detailing the roots and antecedents of the innovation and thereby placing the constraint-induced technological departure in a broader context. Thus, we remain somewhat in the dark about the processes of innovation that constraints tend to promote. This study uses a detailed, longitudinal case study of copper smelting to describe how constraints promoted innovativeness in this well-documented but rarely fully analyzed case. We show that the adoption of existing technological ideas, here diffused worldwide, is an important part of constrained innovation.

A major reason why the relationship between constraints and innovations attracts interest is because constraints can theoretically act as "focusing devices" (Bradshaw, 1992; Hughes, 1983; Rosenberg, 1969) that attract inventive attention to a specific problem. Some extant research suggests that such focus may produce solutions that would have not been invented otherwise (Goldenberg et al., 2001; Moreau and Dahl, 2005; Ward, 2004), that are functionally superior to non-focused efforts (Gibbert and Scranton, 2009; Popp, 2006), or, at least, produce similar results but faster and with fewer resources (Lampel et al., 2012; Gibbert and Scranton, 2009; Hoegl et al., 2008; Weiss et al., 2011).

The premises underlying these arguments are that inventions, or at least important ones, require specialized inventive efforts, such as R&D investments, and involve a conceptual leap of ingenuity that separates the innovation from the existing state of the art. The latter premise is implicitly accepted in all research that defines innovations as something novel, because novelty is generally defined as being something unusual to the context under consideration. Typically, innovations are also seen to involve more or less radical breaks from the traditions of the field. For example, frequently quoted works use words and phrases like "discontinuities," (Foster, 1985), "changes in core technological architecture" (Henderson and Clark, 1990), "launching new technology versus making progress along established path (Christensen and Rosenbloom, 1995), or that "radical exploration builds upon distant technology that resides outside of the firm" (Rosenkopf and Nerkar, 2001).

Flash smelting, the technology we are studying in this article, is often mentioned (e.g. Habashi, 1993, 1998; Särkikoski, 1999; King, 2007) as an example of a breakthrough or radical innovation in the classical sense of the word (Henderson and Clark, 1990). We wish to add the historical perspective to the emergence of this technological innovation. Hence, our case study spans more than a hundred years and details the development of copper smelting around the world including a company not well-known outside the mining industry that became a major innovator in copper smelting: Outokumpu in Finland.

5.2 Calibrating the Role of Resource Constraints in Innovation

As stated previously, constraints can be thought of as focusing devices that direct attention to a particular problem. The often-unstated assumption of research on constrained innovation is that constraints allow or force conceptual leaps of ingenuity to happen. Presumably, these leaps wouldn't happen without the constraints, so the resulting innovation cannot, ipso facto, be obvious to a member of community of knowledge. However, if we accept that innovations tend to be incremental improvements of existing state of the art, the view that constraints induce innovation and, specifically, that constraints induce radical innovation or "out of the box thinking" may need a slight rethink. We do not need to discard the concept of focusing devices, and we are not arguing that constraints do not focus attention to particular problems or promote ingenuity on occasion. Instead, we argue for two things: first, for a more nuanced and historically informed study of examples used in innovation literature. Second, we extend the argument made by e.g. Hoegl et al. (2008) and Weiss et al. (2011) regarding financial constraints to the domain of non-financial constraints and argue that constraints by themselves are largely a neutral factor in the development of innovations: they have the capability both to help and to hinder technological development, but what actually happens depends on contingent factors.

This dichotomous nature of constraints on innovation is clearly visible from wildly diverging research results, some claiming that constraints generally hinder innovation (e.g. Amabile, 1996; Damanpour, 1991; Nohria and Gulati, 1996) and others assigning them a more ambivalent or even positive role (e.g. Arthur, 2009; Gibbert and Scranton, 2009; Gibbert and Välikangas, 2004; Hoegl et al., 2008, 2010; Katila and Shane, 2005; Lampel et al., 2012; Mone et al., 1998; Nonaka and Kenney, 1991; Välikangas and Gibbert, 2005; Weiss et al., 2011). We believe that an important reason why such contrasting viewpoints can be empirically supported is because these studies have only rarely accounted for the "prehistories" of technology examples they use to make their case. What appears to have the decisive influence is the nature of technological development prior to the imposition of a constraint, and in particular, whether such early development has "primed" the innovation environment with parallel, multiple, relatively small incremental advances - a dynamic bearing some similarity to "punctuated equilibrium" models of organizational change (e.g. Romanelli and Tushman, 1994). Our claim is therefore that constraints generally spur innovation if and only if the components required for the "constraint-induced innovation" already exist and are widely known within the community of knowledge. Thus, constraints may not be very good at producing completely new-to-the-world technological innovations, and hence they are not very good drivers of technological advance per se: partly because constraints by definition cause a problem that needs to be solved relatively quickly, they tend to be poor at inducing time-consuming and fundamentally risky, highly exploratory R&D on novel solutions.

However, constraints can be powerful incentives for overcoming switching costs, first-mover disadvantages and other barriers to adoption of already developed but less than completely adopted technologies (e.g. Montalvo, 2008; Nemet, 2009; Popp et al., 2010). In this way, constraints can act as very efficient distributors of technologies that have already been commercialized, or are near commercialization, and it is primarily in this sense that constraints drive the evolution of technology. In the rest of this paper, we present a historical case study that seeks to understand one particular constraint-induced radical innovation with the help of its prehistory.

To examine our theoretical proposition, we now turn to an extended case study of copper metallurgy. The 20th century saw extensive developments in the technologies used to wrest usable copper in greater and greater amounts from increasingly poor ores. By 1990, the technologies that had dominated copper smelting for over 200 years were all but dead and replaced with technologies largely brought to use during the second half of the century. Several of these innovations were and still are hailed as landmarks in metallurgy. In this case study, we focus on what has been sometimes lauded as one of the most important metallurgical breakthroughs of the 20th century (Särkikoski, 1999): the technology for flash smelting of sulfide ores. Flash smelting was first realized in commercial scale in 1949 by Outokumpu, a small copper mining company in Finland, and a few years later in a slightly different form by nickel giant Inco in

Canada.

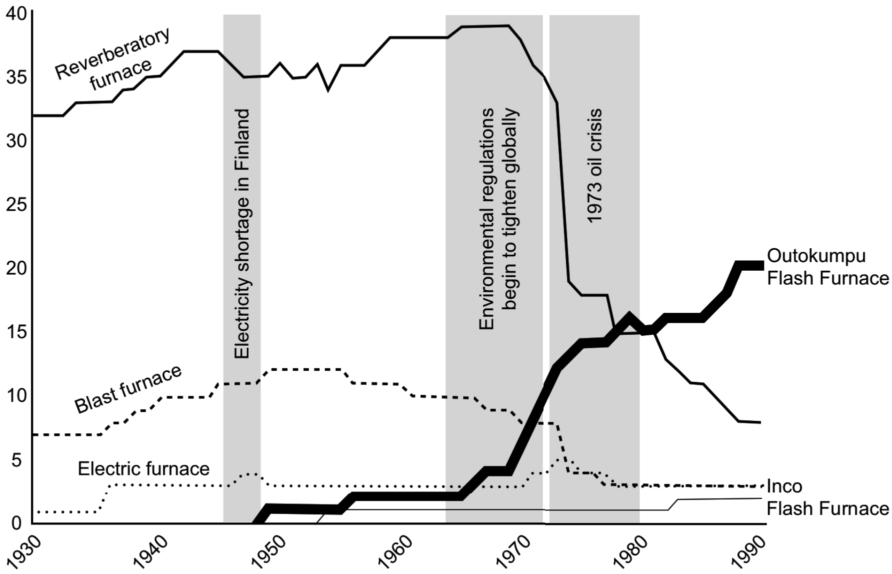

Figure 5.1: Furnace types used by the world's copper smelters. Data from U.S. Bureau of Mines Mineral Yearbooks 1931-1990 and from metallurgy textbooks (Biswas and Davenport, 1976; Davenport et al., 2002; Newton and Wilson, 1942). N.B. Figures refer to number of smelters, not the number of smelting furnaces, as individual smelters often used multiple furnaces, sometimes of different types.

The effects of Outokumpu's and Inco's advances were certainly significant, even radical. Replacing the previously dominant technology while simultaneously greatly improving energy efficiency, increasing production and reducing harmful emissions is no mean feat. But were these technologies really radical breaks from existing practice, requiring significant ingenuity, as argued by some (Särkikoski, 1999; Habashi, 1993)? Or were they just logical culminations of steady, incremental accumulation of knowledge?

5.3 A note about the methodology

The historical case study presented here is based on a variety of sources, of which only some are cited in the text. In addition to cited works, the archives of the leading industry periodicals *Journal of Metals, Transactions and Bulletins of the American Institute of Mining Engineers,* and *Engineering and Mining Journal* were extensively used, in addition to a variety of modern and historical textbooks and research articles dating back to 1847. Year-to-year information and background about copper mining industry was also obtained from annual Minerals Yearbooks published by the U.S. Bureau of Mines (after 1995, by the U.S. Geographical Survey). Yearbooks from 1931 to 1990 were particularly valuable. In addition, interviews with the Materials Engineering faculty of Helsinki University of Technology (now Aalto University School of Science and Technology) and senior personnel from Outotec, the current owner of the flash smelting technology developed by Outokumpu, were used for valuable background information.

The case was originally researched because flash smelting provided a rich history of an innovation developed as a direct response to resource constraints; it was not specifically chosen to support the argument outlined in this paper. Although restrictions on length prevent us from providing more examples, it should be noted that several other technologies studied by the authors show similar dynamics (e.g. Korhonen, 2013).

5.4 The accumulation of innovation increments in copper smelting over time

The prehistory of flash smelting of copper reaches back to the mid-1800s, when the spreading electrification greatly increased the world's appetite for this ductile, corrosion resistant and conductive metal. By 1880, the process of industrial-scale copper production was relatively standardized across the planet: the ore was first crushed to a suitable size, then usually roasted in a special roasting furnace to remove most of the sulfur, then smelted in a smelting furnace to remove gangue and iron and produce low-grade copper (so-called copper matte), and finally converted (purified) in yet third furnace (Figure 2).

By the turn of the century, two types of smelting furnace provided the majority of world's copper (Peters, 1898b). The older vertical shaft or "blast" furnace, dating from the middle ages, was well suited for relatively rich ores that yielded solid lumps of copper-bearing sulfites. Its somewhat younger competitor, horizontal or "reverberatory" furnace, could process finely ground ore concentrates that were increasingly what the poorer copper mines could produce, and did not require purified and expensive coal-derived coke that blast furnaces depended upon.

To metallurgists, however, the choices were far from satisfactory. Both furnaces used considerable amounts of fuel, averaging at about 60 percent of the total cost of copper smelting (Peters, 1898a). What

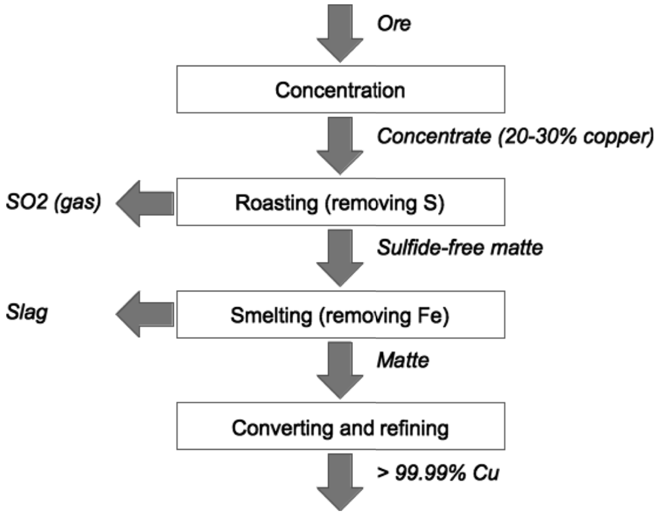

Figure 5.2: Basic copper smelting process.

made this particularly galling was the fact that the copper ore itself seemed to contain a significant source of energy: theoretically, the sulfur in the ore could be burned in the furnace, instead of wasting its heat content in the pre-furnace step of roasting. As one textbook on copper metallurgy, originally from 1877, lamented:

> "In treating ordinary sulphide ores… we are at great pains to burn and destroy, more or less perfectly, the very sulphur and iron that form nature's fuel to melt the ore itself. ... It is as though we employed the contents of our coal-bins to burn up a large portion of our coke-pile, so that we could get at the residue of it more conveniently." (Peters, 1898a, p. 376)

In about 1866, a Russian engineer named Semennikov made the first recorded recommendation for using sulfur as fuel (Sticht, 1898, p. 400). In this, he was inspired by the example of steel Bessemer process, dating from 1855 and utilizing similar principle in the production of steel. As an example of either rapid spread of ideas or independent discovery, a mention of the idea can be found in an American textbook published in 1870 (Särkikoski, 1999). In due course, experiments were made in utilising the sulfur's potential. The first concrete proof of possibility came in 1878 (Sticht, 1898). The result, so-called "pyritic smelting" was a logical, straightforward extension of blast smelting process: a blast furnace "scarcely original to the process," to quote Sticht (1898, p. 417), was loaded with ore rich in sulfides, and some coke added to help ignite the sulfur. The method promised to save up to 40 percent of the fuel costs, which was a considerable advance. Furthermore, crushing and roasting processes and their associated equipment and personnel, costing anything between 17 to 50 percent of the total smelting cost, could be dispensed with as well (Peters, 1898a). First industrial scale plants were erected already in 1881, and the process understandably attracted considerable interest (Sticht, 1898). However, it was difficult to control, yielded poor-quality copper matte and, most damningly, was very particular in regard of the ore used. Ore of suitable chemical composition and rich enough to be mined in lumps was yielded by some mines, but these ore bodies were largely exhausted by 1930. As a result, the pyritic smelting and its derivatives gradually fell out of use (Mäkinen, 1933). Therefore, from ca. 1890 to 1950, the reverberatory furnace was increasingly the go-to method for smelting copper, although a few electric smelters were built in areas where abundant electricity was cheaply available (Newton and Wilson, 1942, p. 146).

The idea of using sulfur as fuel did not vanish, however. In 1897, the first patent explicitly describing a method for "autogenous" smelting of finely ground ores was granted in the United States (Bridgman, 1897; Staff of Inco Mining and Smelting Division, 1955). The patent, granted to a Chicagoan inventor Henry L. Bridgman, describes a largely conventional horizontal reverberatory furnace, where finely ground ore concentrate is ignited in air in place of conventional fuel.

It is probably no coincidence that Bridgman's patent appeared in the 1890s. Because ore bodies, by and large, were getting poorer and poorer, novel techniques for pre-processing copper ore had to be developed at the same period. Especially relevant to Bridgman's invention, one of these concentrating techniques under development at a time, froth flotation, could produce extremely fine, almost dust-like and relatively rich concentrate. Igniting dust-like concentrate would be significantly easier than igniting more or less gravel-like ore from earlier mines; in fact, it seems that Bridgman's patent was granted mere years after the first adoption of copper production processes that could support it!

Nevertheless, one major difficulty remained. Compared to pyritic smelting, too much heat was lost in flue gases. The process could thus only reduce fuel use, not eliminate it altogether. What's more, the fuel savings may have been as little as 5 percent (Newton and Wilson, 1942). This and Bridgman's death in 1900 seem to be key reasons why there is no mention of Bridgman's autogenous furnace ever being used in an industrial scale.

Only a few years later, a group of metallurgists working for Anaconda Copper Company in Montana were granted another patent on autogenous smelting (Klepinger et al., 1915). The key improvement over Bridgman's patent was an addition of a heat exchanger: this re-used heat from the furnace flue gases to preheat incoming blast air and thereby greatly improved the heat balance of the process. Again, the invention was scarcely radical. The developer of pyritic smelting, John M. Hollway, had suggested in 1879 that heat of flue gases could be used to preheat the blast (Sticht, 1898), and a thorough discussion of pyritic smelting in a textbook published one year after Bridgman's patent (1898) noted that "all metallurgists are well aware of the great effect produced by even a slight increase of temperature [achievable by preheating the blast] on the rapidity and energy of chemical reactions [...] " (Peters, 1898a, p. 383). In a similar vein, Sticht writes in 1893 that

> "Locally, much has been made by the uninitiated, in the regions where the [pyritic smelting] process is in use, of this application of a preheated blast as a startling novelty in the smelting of the more precious metals [i.e. copper]. In truth, however, *hot blast, in the course of its nearly sixty years of uninterrupted employment for metallurgical purposes in Europe, has long ago found its way into the smelting of the more valuable metals and, in fact, is theoretically urged for introduction wherever the nature of the metals treated permits of its use.*" (Sticht, 1898, p. 412, emphasis added)

Although the text does does not explicitly mention Bridgman's horizontal furnace design, the principle of "recycling" heat from the flue gas to preheat the air blast would have been self-evident to any competent metallurgist. Preheating blast air had been invented in 1828 by James Beaumont Neilson in Scotland (Gale, 1967, pp. 55-58). E. A. Cowper and Sir Carl Wilhelm Siemens took the logical step of recovering heat from flue gases in 1850s, with patents for "regenerators" granted in 1856 and 1861 respectively (Gale, 1967, pp. 74-77, 98-100). In other words, what Klepinger et al. created was not so much a novel invention, but rather the logical improvement for the earlier process. It may be surmised that Bridgman might have himself made the same improvement, had he not died just three years after patenting his original furnace design.

As patent citations were a later innovation, it is difficult to obtain concrete proof that Klepinger et al. were aware of Bridgman's patent. However, Bridgman was not an isolated inventor, but an active member of the American Institute of Mining Engineers (AIME), the premier professional body for mining and metallurgy (see e.g. mentions of his work in *Engineering and Mining Journal*, Oct 10, 1891). Furthermore, the *Bulletin* and the *Transactions of the AIME* and other periodicals like *Engineering and Mining Journal* covered extensively any new developments and patents relevant to the industry. It seems very highly unlikely that knowledge of prior art and archives of these periodicals were not available to Klepinger's group, working as it did for one of the largest copper mines in the United States. In general, the tightly knit, relatively small network of professional metallurgists, bound together by mutual interests and often known by name to each other, and the speed with which ideas in the mining and metals industry spread across the world seems to have precluded truly independent developments. Instead, the inventions were more or less collective (Allen, 1983): even competitors exchanged information about their processes and experiments relatively freely (see also Särkikoski, 1999, for examples of this network in copper industry).

5.5 World-wide Experimentation

There is no evidence that even Klepinger et al's furnace or later, slightly different design by Horace Freeman (Freeman, 1932) were ever realized in commercial scale (Bryk et al., 1958). The idea that fine concentrate dust produced by froth flotation could in principle be ignited and used to smelt the ore was well established, however, and several important developments occurred during the 1930s. First, in the spring of 1931, Frederick Laist and J. P. Cooper, again from Anaconda Copper Company, performed an experiment with a down-draft roasting shaft mounted over a small reverberatory furnace (Cooper and Laist, 1933). The concentrate was fed to the vertical roasting shaft and ignited in air. The fuel consumption was decreased by 60 percent, and the experimenters reported that fitting shaft roasters to standard reverberatory furnaces would be reasonably expected to increase the smelting capacity by 50-100 percent without increases in fuel consumption.

Another experiment along the same lines was conducted in the Soviet Union. Bryk et al. (1958) refer to a series of tests performed in 1935, in which concentrate-air suspension is injected into shaft furnace built over a reverberatory-type vertical settler bath. However, wear of furnace bricks was intense and molten flue dust had tended to clog up the flue. In around 1937, a French-owned Societe Mines du Bor also tried autogenous smelting with vertical shaft furnace in Bor, Yugoslavia (Bryk et al., 1958; Särkikoski, 1999, p. 113). However, the results were negative and the outbreak of the war ended the experiments. Although the former experiment was apparently reported in Russian periodicals, it seems that these experiences were largely ignored in North America.

Perhaps the most important development of the decade, however, was the publication of an article by T.E. Norman in 1936 (Norman, 1936). Working for nickel giant Inco in Canada, he discussed the theoretical aspects of smelting copper concentrates without the use of extraneous fuel. This research confirmed that the heat balance of the process would not suffice, unless remedial measures were taken: too much heat was absorbed by inert nitrogen introduced by the air blast. If, however, the concentrate were burned in an atmosphere of 40-95 percent oxygen, then there would be less material to absorb the heat evolved. A higher temperature could be attained, and sulfide ores would melt. The theoretical discussion was accompanied with calculations based on smelter feeds at three large smelters in North America, showing that fully autogenous smelting was, at least in theory, entirely possible.

By that time, the result seems to have been almost self-evident to most metallurgists. The benefits of oxygen were well known even in the 1800s (Davis, 1923), the only problem having been affordable tonnage production of the gas. However, around the turn of the century major steps in solving the problem were taken by almost simultaneous developments of air liquefaction process by Linde in Germany and Claude in France (Greenwood, 1919). The nitrogen produced from liquefied air had important uses in munitions and fertilizer industries, and tonnage production of oxygen was an established industry by the 1930s. As a metallurgy textbook published in 1942 states in an almost offhand discussion of Norman's research,

> "Provided that a suitable furnace could be designed which would be as satisfactory as present equipment, the factor that would be of primary importance would be the relative costs of fuel and oxygen." (Newton and Wilson, 1942, p. 161)

No mention is made of any insuperable difficulties: Autogenous smelting was now seen as little more than an exercise in practical engineering, to be put into use once the relative costs of oxygen enrichment are below fuel costs. In the latter half of the 1930s, several inventors had indeed experimented with different technologies and patented air- and oxygen-based furnaces (Haglund, 1940; Zeisberg, 1937).

But copper-smelting technology was not the only force on the march. On September 1, 1939, the Second World War broke out in Europe. As industries round the world geared for war, productivity and reliability were what mattered. Uncertain, untested technologies had to wait, as long as "[...] there was a war to win" (Queneau and Marcuson, 1996, p. 14).

5.6 The Birth of Autogenous Smelting in Finland

After the war, a small Finnish copper mining company Outokumpu found itself in dire straits. Founded in 1914 to exploit an eponymous copper deposit discovered in 1910 in eastern Finland and 100 percent state-owned since 1924 (Kuisma, 1985), it had completed the world's largest electric copper-smelting furnace in 1936, utilizing electricity from a new, close-by Enso hydropower plant (Newton and Wilson, 1942; Särkikoski, 1999). The smelter produced valuable copper until summer 1944, when a Soviet attack forced it to relocate to the western coast of the country. The facility had almost been brought back to full operation when the armistice between Finland and Russia went into effect. One of the stipulations of the armistice required Finland to cede major parts of eastern Finland, including the important Enso and Rouhiala hydropower plants, to the USSR. In one fell swoop, one third of the electricity generating capacity of the country was lost (Kuisma, 1985, p. 124). Combined with the demobilization of the army, the gradual return to civilian life and, in particular, the exacting war reparations (amounting to 61 percent of total exports in 1945, for example) that put heavy strain on the domestic industry to increase its production, the inevitable end result was a steep rise in electricity prices. Outokumpu's electric smelter, which alone accounted for some 3 percent of the country's electricity use (Kuisma, 1985, p. 162), naturally suffered as its electricity costs saw an almost five-fold increase between 1946 and 1948 (Kuisma, 1985, p. 124).

A state-owned company producing not just an extremely important export product and perhaps even more important war reparatory deliverable (copper), but also some useful raw material for domestic industry (iron) and a necessary ingredient for paper and fertilizer manufacturing (sulfur) might have been able to commandeer the scarce electricity by arguing that its wares were more important than heat and lighting. However, the company's directors did not press the issue. In fact, even before the State Electricity Commission formally inquired whether Outokumpu could limit its electricity use in late 1945, a crash program to develop another smelting method had been started (Särkikoski, 1999, pp. 99-100). In just three months of work by a core group of three to four engineers, the work produced an alternative. Back-of-the-envelope calculations suggested that flotation concentrate from the eponymous Outokumpu copper mine could be ignited in air, and if the heat from the combustion could be recycled back as preheated air, the energy balance of the process would stay positive — or at least good enough so that the difference could be economically made up with scarce fuel oil. The hunt for scarce construction materials began in 1946, and in February 1947, less than two years after the start of the project, the pilot plant roared to life (Särkikoski, 1999; Kuisma, 1985). After few days of adjustments, true autogenous smelting was achieved: as long as the finicky heat exchanger worked, the plant did not need extraneous fuel. The Outokumpu flash smelter, whose direct descendants would eventually be responsible for smelting more than 60 percent of the world's primary copper, was thus born. Planning for full-scale furnace began in September 1947, and building commenced three months later (Kuisma, 1985, p. 126). By 1949, the method was in commercial use, although old electric furnace accounted for a third of the production as late as in 1953 (Kuisma, 1985, p. 127).

The pre-war developments, the speed with which Outokumpu's project proceeded despite post-war difficulties in obtaining even basic construction materials, and the fact that there is no evidence of company's directors even seriously considering other options such as demanding priority for electricity or import credits for coal, strongly suggest that the discovery of the reverberatory furnace was "in the air" at the time. Outokumpu had had no history to speak of in the field of technological innovation, but all the evidence suggests that its engineers were very well informed of developments in copper smelting elsewhere. The company had been importing advanced mining and metallurgical technologies and skilled personnel since its founding in 1914, and its culture, partly a product of conscious attempt to develop its own skill set and partly a product of wartime necessities that forced it to do so, emphasized learning and improvising to keep the wheels turning. Särkikoski (1999, p. 71) summarizes the philosophy of Outokumpu's long-time managing director, Eero Mäkinen (state-appointed controller since 1919 and managing director from 1921 to 1953) as "one should strive to do the best oneself, but if this does not succeed or if there is not enough time, it is not shameful to acquire the expertise from someone else."

The managing director of Outokumpu and the *éminence grise* of the flash smelter, Eero Mäkinen, had a PhD in geology, a M.Sc. diploma in mining engineering, and had worked for years to forge connections between Finland's fledgling mining engineering community and centers of learning abroad (Kuisma 1985, 2008). He saw the development of Outokumpu from a simple commodity ore mine to value-added finished goods producer where "every gram of ore promotes Finnish production" as a part of a larger production program for the industrialization of Finland, which was a poor agrarian country at the time (Särkikoski, 1999, p. 71). In his view, developing the company was synonymous with patriotism, and lack of ardor in pursuing increased domestic capability was tantamount to treason. His attitude may be best illustrated by a private letter to a key member of parliament in 1924, when the government's financial affairs committee contemplated renting the Outokumpu copper mine to foreign interests that would probably have had little interest in building refineries in Finland: in a vituperative letter, he threatened to "gather all the dynamite he could find in the mine to the [financial committee's office] basement and blow the committee sky high" if the mine had been rented out (Kuisma, 1985, p. 62).

However, he also emphasized that there were no shortcuts to knowledge (Särkikoski, 1999, p. 71) and acted accordingly, taking active part in higher education of mining engineers and metallurgists. While serving as a managing director, Mäkinen went as far as to author one of the first comprehensive treatments of mining and metallurgical technology in Finnish (Mäkinen, 1933). (The text includes a brief but well-informed account of pyritic smelting of copper.) Before the war, Outokumpu gave financial aid to hire foreign specialists to teach in the Helsinki University of Technology, and engineers and geologists from Outokumpu were regularly sent abroad to learn from best available practices (Kuisma, 2008; Särkikoski, 1999). The experience of Petri Bryk, the first inventor in the key patents granted to flash smelting, is illustrative. When he joined the company as a fresh M.Sc. graduate in 1938, the 25-year old's very first assignment, by Mäkinen's orders, was a two-year learning tour of copper refineries in North America (Särkikoski, 2008). This was a remarkable journey at the time, and it is an indication of Outokumpu's (and Mäkinen's) connections within the industry.

These connections and the "can-do" attitude proved their worth when developing flash smelting. The fruit of Outokumpu's labors resembled the Laist-Cooper furnace tested in 1931 in the United States (Cooper and Laist, 1933).[2] A vertical reaction shaft was attached on top of a horizontal settler, greatly resembling traditional reverberatory furnace. Ore concentrate and preheated air would be injected from the top and ignited. A flue collector at the other end of the settler would collect the gases and pass them to the heat exchanger. This, however, would prove to be a very troublesome piece of equipment: in the mid-1950s, the unreliable heat exchanger was in practice eliminated in favor of oil-fired preheaters (Särkikoski, 1999).

As mentioned previously, none of these developments were really novel: besides ideas already introduced within the copper industry, many of the components were in widespread use in other industries, and were consciously modeled after these practical examples (Särkikoski, 1999). Particulate reactions in air suspension were understood thanks to work in coal dust-fired power plants, sulfide burning in suspension was already practiced in the manufacture of sulfur and sulfur dioxide, and heat exchangers for blast preheat had been invented nearly hundred years previously. In a sense, the developer of pyritic smelting, John M. Hollway, had already predicted the likely shape of the flash furnace in 1879. He envisioned a vertical shaft furnace, with a hopper of sulfide ore on top feeding the process. The heat from the flue gases is reused to preheat the blast air, and,

> "If desired, the products could be run direct into suitable reverberatory furnaces, where, after the [matte] had subsided, the slag would be run off while yet in a molten state, and in which the oxidation of the [matte] could be completed." (Quoted in Sticht, 1898, p. 406)

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[2] It is interesting to note that neither the contemporary accounts written by the inventors (e.g. Bryk, 1952; Bryk et al., 1958) nor the patent (Bryk and Ryselin, 1950) mention the Laist-Cooper experiments. It is possible that these experiments were not known to Bryk et al, although the definitive history of Outokumpu flash furnace, written with access to Outokumpu's archives, does mention in passing that the pilot plant built in 1947 was modeled after the Laist-Cooper furnace (Särkikoski, 1999, note 116). As the experiments were reported in one of the leading periodicals of the day, which was certainly read in Outokumpu, and the nearly contemporary account written by the inventors (Bryk et al., 1958) refers to T.E. Norman's 1936 study, which in turn quotes Laist and Cooper, other reasons — perhaps simple forgetfulness — seem more likely. The similarities between Outokumpu design and the Laist-Cooper furnace did not escape contemporary observers, however (Staff of Inco Mining and Smelting Division, 1955). These similarities have been downplayed by later scholars (Habashi, 1993, 1998)) and it is definitely possible that the nvention was entirely independent of Laist and Cooper's work, as the principles were well known and the parameters of the problem greatly limited the scope of practical solutions.

Because of multitude of existing patents describing autogenous smelting, Outokumpu in fact had trouble patenting its invention in the United States (Särkikoski, 1999). What was finally patented was the process direction, from top to bottom in a vertical chamber (Bryk and Ryselin, 1950). The invention may not have been an exact copy of a previously existing design (Habashi, 1993, 1998), but it is difficult to see it as a great conceptual or radical leap upon existing state of the art. The largest leap of faith taken by Outokumpu was the decision to built the first pilot plant: primary metals industry was and is naturally cautious, and investing in 1946 Finland must have been a risky bet at best.

Meanwhile in Canada, the nickel giant Inco had restarted the research that had been rudely interrupted by the war. Based on Norman's work suggesting oxygen as the solution to the heat balance problem (Norman, 1936), the research immediately focused on oxygen flash smelting of sulfide concentrates (Queneau and Marcuson, 1996). A major reason for this focus was Inco's near-world monopoly in nickel; oxygen pyrometallurgy could be more easily adapted to nickel smelting (Brundenius, 2003), although Outokumpu's method would be eventually modified for nickel as well (Särkikoski, 1999; Kuisma, 1985). Suitability for nickel production was obviously attractive to a company that had held 90 percent of the non-Communist world's nickel supplies before the war (Pederson, 2002).

Outokumpu had also considered the possibility of oxygen, but the unavailability of oxygen generators in post-war Europe and the cost of electricity needed to run them had dissuaded them from following the same path (Särkikoski, 1999; Kuisma, 1985). Inco however had access to nearly unlimited cheap electricity from Niagara Falls and, as one of the true giants in the metals industry, almost inexhaustible coffers as well. At the war's end in 1945, its assets were valued (in 2010 dollars) at about US$ 1350 million, its sales stood at $1480 million, and its net income was very healthy $300 million (Pederson, 2002). Compared to Outokumpu, whose total sales in 1945 were some $103.5 million and net profit approximately $15.3 million in 2010 dollars (Kuisma, 1985, p. 442), Inco was indeed a colossus. Despite its resources, Inco's R&D was hampered by long delays caused by the post-war supply problems and high prices stipulated by the dominant supplier of oxygen systems, Linde (Queneau and Marcuson, 1996). Nevertheless, cooperation with another, smaller supplier (Air Liquide) resulted to pilot plant operations starting in January 1947 (a month before Outokumpu's) and commercial operation of new-built furnace starting on January 2, 1952 (Staff of Inco Mining and Smelting Division, 1955; Queneau and Marcuson, 1996).

By that time, Outokumpu had over two years of commercial-scale although by no means trouble-free experience in flash smelting, but with a significantly different process. Outokumpu's process originally focused on saving as much extraneous fuels as possible with "true" autogenous smelting; Inco's flash furnace utilized electricity-generated tonnage oxygen primarily to greatly increase the productivity and only secondarily to decrease the fuel costs of contemporary reverberatory furnaces (Bryk et al., 1958; Gordon et al., 1954; Staff of Inco Mining and Smelting Division, 1955; Saddington et al., 1966). Interestingly, as Figure 3 shows, the Inco method was even from the start more energy efficient than Outokumpu's method; the difference was that Outokumpu's original method did not need expensive and, in war-ravaged Europe, scarce oxygen generators. Instead, extra energy was introduced first through heat exchangers, and after these proved troublesome in practice, from simple fuel oil burners.

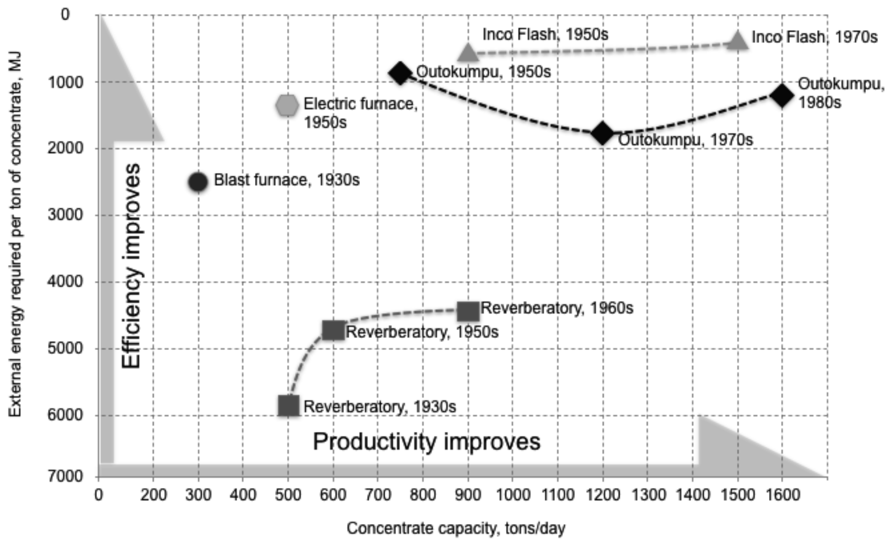

Figure 5.3: The development of copper smelting furnaces in the 20th century. (Data from Biswas and Davenport, 1976; Davenport et al., 2002; Newton and Wilson, 1942).

What is common to both methods, however, is that they were hardly great conceptual leaps diverging significantly from existing practice. They were the almost logical outcomes — pinnacles, if you will — of a century of developments in various complementary fields, including metallurgy, chemistry, thermodynamics, cryogenics and the like. Although it could be claimed that the inventions look logical and inevitable only in hindsight, the contemporary sources give a strong impression that the inventions, even down to their specific details, were anticipated decades before developments in complementary technologies such as froth flotation and oxygen generators made their commercial realization practical. Clearly, several copper smelters had the opportunity, the means, and perhaps even the motive to invent the flash furnace; to take just one example, the Anaconda Copper Company, which sponsored Laist and Cooper's experiments, was already close to the solution by 1930s, before experimentation was put on hold first because of the Great Depression and then because of the war (Newton and Wilson, 1942; Queneau and Marcuson, 1996). Commercialization required large investments (in 1947, building the commercial-scale Outokumpu flash furnace was estimated to cost $30 million in 2010 dollars, representing some 12 percent of the firm's revenues at the time) and the mining industry was notoriously conservative as long as traditional solutions served them well enough (Kuisma, 1985). In the aftermath of the Great Depression and again after the war, the problem for copper producers in general was how to cope with overcapacity, not how to increase the capacity by new furnaces.

Therefore, while crediting the inventions to contingent historical factors would overlook the long history of copper metallurgy, the inducive factors, such as the annexation of Finnish hydropower plants by the Soviet Union, or the availability of cheap hydropower and oxygen generators in Canada, help explain why precisely Outokumpu and Inco eventually became the inventors of flash smelting. This seems to have had less to do with any specific capabilities or resources of these two companies (albeit Inco's strong financial position certainly helped it to experiment and Outokumpu's interest in worldwide developments were surely conducive to innovation as well). Instead, the events seem to have more to do with historical and local contingencies. Interestingly, whereas scarce electricity was the key constraint driving Outokumpu's design decisions, it could be said that abundant electricity was one of the key factors influencing Inco's choice of oxygen-based process — which turned out to be the better of the two process choices.

Table 5.1: Outokumpu and Inco in comparison.

	Outokumpu	Inco
Sales in 1945 (million 2010 USD)	103.5	1480
Net profit in 1945 (million 2010 USD)	15.4	300
Primary product	Copper	Nickel
Market share in primary product	ca. 1-2%	ca. 90%
R&D experience	Some during the war	Extensive, from 1906
Ownership	State-owned (but run as a commercial venture)	Private, traded in NYSE
Prior smelting technology	Electric	Mostly reverberatory electric
Flash smelting developed primarily to:	Produce copper without external fuels	Improve productivity
External energy required per ton of concentrate	ca. 900 MJ	ca. 700 MJ

5.7 Discussion and Conclusions

Our study gives credence to the argument that radical innovation, induced by necessity, must benefit from existing innovation increments that are already invented and distributed in the innovation ecosystem, so that they are usable for the innovator company such as Outokumpu. The worldwide experimentation contributed to technological innovations that were available for the well-informed when under duress. Outokumpu had at its service a number of highly skilled experts who knew about technological developments and were able to apply them once the energy shortage forced the circumstances. However, it took the energy crisis after Second World War in Finland for the engineers to recombine these elements (Arthur, 2009; Fleming, 2001; Hargadon and Sutton, 1997; Murray and O'Mahony, 2007) into a new technological architecture for copper smelting.

Although the details of the further development and the eventual "triumph" of Outokumpu furnace are beyond the scope of this paper, it should be noted that the system is currently the single most common smelter furnace in copper smelting, accounting for 30-50 percent of the total copper smelting capacity in the world (Moskalyk and Alfantazi, 2003), and is used for other metals (e.g. nickel) as well. The invention and the efforts to license it to other smelters also spawned a successful mining technology enterprise Outotec, which was spun out from its parent company in 2006. The widespread use of flash smelting may be largely credited to tightening environmental regulations, particularly sulfur dioxide emission limits, which were easier to achieve with a flash furnace, and to the 1973 energy crisis, which made competing electric furnaces in particular expensive to operate (Biswas and Davenport, 1976; Davenport et al., 2002; Särkikoski, 1999).

However, it is also instructive to note that the reasons why Outokumpu and not Inco method "won" this race has much more to do with the different incentive structures and licensing strategies pursued by these two very different companies (Brundenius, 2003), rather than with the technical advantages of one technology over another. In fact, Inco's method remained in many ways technologically superior. As late as in 1976, a textbook of copper metallurgy (Biswas and Davenport, 1976) listed no less than five significant advantages the Inco method possessed over Outokumpu's method. The authors found the success of Outokumpu's method "somewhat surprising," because "[...] it appears that the Inco process is the better from both a technical and economic point of view" (p. 170).

The efficiency and productivity advantages were diminished, but not eliminated, only when Outokumpu finally adopted oxygen injection in the early 1970s (Kojo and Storch, 2006). Brundenius (2003, pp. 24-39) argues convincingly that the reason why Inco did not license its technology was to protect its extremely lucrative advantage in nickel smelting, for which its method was particularly suitable. After all, technology sales were not big business: In 1956, Outokumpu's first licensor paid just $1.3 million in 2010 dollars for a complete smelter design (Särkikoski, 1999). Hence, the risk of losing control of the technology may not have been a gamble worth taking for a company that was at the same time raking in revenues of some $3700 million per year, in 2010 dollars, chiefly from sales of nickel (Pederson, 2002). As the saying went, Inco was not just a nickel company, Inco was nickel; by-products of nickel and technology sales were at best sideline business. Personal differences between Inco and Outokumpu management may also have played a part. Petri Bryk, an accomplished metallurgical engineer and the first inventor of flash furnace, was named Eero Mäkinen's successor as the CEO upon the latter's sudden death in 1953, and until mid-1960s, selling "his" flash furnaces seemed to be a sort of a pet project — even a hobby — he indulged in (Kuisma, 1985). He may also have been motivated by monetary considerations: he received a substantial personal income from license fees, to the extent to making him the top earner in Helsinki, Finland's capital, in the early 1970s (Kuisma, 1985). In contrast, Inco's top management, though astute, was arguably less incentivized to selling "its" technology to outsiders (Pederson, 2002).

What's striking about Outokumpu's constraint-induced innovation is how close it was to practical use in any case: had Outokumpu not developed flash smelting and had Inco retained its own patent for its own use, it's more than likely that another copper manufacturer would have invented a furnace functionally similar to Outokumpu's within the next decade at the latest. If this had happened, it seems likely that the end result would have been much closer to Inco's patent or the eventual oxygen-enriched Outokumpu furnace of the early 1970s: oxygen injection provided so many advantages that its adoption was all but inevitable.

In conclusion, based on our historical study of copper smelting over the last 200 years, ingenuity is indeed needed under resource constraints. However, this ingenuity appears to be about combinatorial capability, being able to efficiently track the existing distributed innovation increments in the ecosystem and recombine them into a working, even if at first experimental, solution (see also Baker and Nelson, 2005; Garud and Karnoe, 2003). The right moment for such new architecture building may be induced by a shock or other severe resource constraint. We extrapolate that absent the innovation increments or components accessible in the ecosystem, resource constraints do not seem to produce innovation but more likely result in poverty or the deterioration of economic circumstances. Resource constraints thus seem to be capable of both helping and hindering innovative efforts, just as Hoegl et al. (2008) and Weiss et al. (2011) have noted in the context of financial constraints. Necessity stimulates innovative efforts but results in ingenuity only when the opportunity for recombining innovation increments exists in the historical technological context, which, as described in this paper, may be global in nature. However, necessities may induce innovation in unexpected places — like Finland. In short, constraints seem to more capable of bringing about novel innovators, rather than novel inventions; necessity is a mother of inventors, not inventions.

5.8 Acknowledgements

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Chapter 6

Essay III: Tolerating the intolerable

Flash smelting of copper and the construction of technological constraints

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6.1 Introduction

Just before New Year's eve in 1944, Eero Mäkinen, the managing director of small Finnish copper producer Outokumpu sat down to pen a letter that instructed his staff to begin developing something the world had never seen before.[1] In the letter, Mäkinen warned that Outokumpu's single electric smelting furnace might not be able to serve the company for much longer due to lack of reliable electricity supply. He also noted cursorily that the obvious alternative, smelting Outokumpu's ore with heat generated from fossil fuels, would also be problematic since it would make the smelter dependent on imported coal. In conclusion, he devoted most of the letter detailing the staff to look into a novel alternative: smelting copper using heat liberated from burning the ore itself.

Only four years later, this line of inquiry resulted to Outokumpu being the first copper smelter in the world to adopt so-called "flash smelting" practice for commercial use. In this practice, the energy

[1] Letter from Eero Mäkinen to John Ryselin, 30.12.1944. Folder Kirjeenvaihto 1944 A-U, K31 (OKA). Sources and explanations for abbreviations in parenthesis are found in the Bibliography.

required came from burning sulfur, a component of common copper ores. In principle, the method did away with the need for extraneous energy, an improvement so radical that even today, variations of this process produce the majority of world's primary copper.[2] A narrative well entrenched in the history of metals and mining industry suggests that this innovation resulted from a constraint imposed by the electricity shortage in post-war Finland: Outokumpu simply had no other options and was therefore compelled to invent something radical — or to perish.[3] Seemingly, the intolerable constraint had radically shaped an entire industry for decades to come.

But how intolerable this constraint actually was, and how the constraint itself became a constraint? In this article, I extend the work of earlier historians by examining in more detail the birth of flash smelting and the question "what makes constraint a constraint?" I argue that as far as they influence technological change, even supposedly inflexible physical constraints, such as lack of coal seams in Finland, are to a large extent social constructions.

Evidence presented in this paper suggests that instead of being forced to make a breakthrough and then miraculously realizing it, Outokumpu in fact had at least three other credible alternatives at its disposal. Furthermore, any of these could have been argued to be prudent and possibly even more prudent choices for a company in Outokumpu's position. Finally, I present evidence that what was seen as a supposedly intolerable constraint in 1944-45 had been seen as an entirely tolerable necessity only some years earlier, and that this shift in opinion had more to do with changing perceptions of the feasibility of different technological alternatives than with actual changes in Outokumpu's operating environment. The evidence suggests that many, though certainly not all, of the constraints constraining our choice of technological systems contain a significant socially constructed component.

The presence of a socially constructed component within perceived constraints implies that constraints could be renegotiated, at least to an extent. In this case, even a supposedly unyielding constraint, lack of energy supplies in Finland, turned out to be a quite malleable concept in reality. Whenever the desired technology so required, this constraint was renegotiated, downplayed or entirely ignored, only to resurface as a somewhat post hoc rationalization

[2] Moskalyk, R. & Alfantazi, A. Review of copper pyrometallurgical practice. Also author's interviews with successor company Outotec personnel.

[3] For examples, see the histories of Outokumpu and flash smelting such as Annala, V., Outokummun historia 1910-1959; Kuisma, M., Outokumpu 1910–1985; and Särkikoski, T., A Flash of Knowledge. For similar narrative from an outsider, see e.g. Habashi, F, History of metallurgy in Finland: the Outokumpu story, and Habashi, F., The Origin of Flash Smelting.

for decisions already made. Likewise, when the needs must, even the intolerable may turn out to be surprisingly tolerable after all.

Studying constraints and how they are used in rhetoric about technology is an important topic for technology studies for at least two reasons. First, much of the history of technology tells us that physical constraints, such as availability and cost of components, raw materials or labor, have greatly shaped the evolution of technology. With the rise of social study of technology, we have learned that mental constraints, such as accepted frames of reference, matter as well. Concepts such as constraints have an important role in helping to explain questions such as the extent of technical variation, the emergence of dominant designs, the rate and direction of technological change, and occurrences of technological discontinuity. However, few if any studies so far have attempted to explore the nature of constraints themselves. As far as their effects on technological change and the evolution of technology have been studied, they have been largely treated as exogenous factors that affect technologists either as physical constraints (e.g. lack of specific resources) or as mental constraints ("thinking inside the box").[4]

Second, examining the nature of constraints is meaningful not only for historians but for the world as a whole. We live in a time when both technological systems and constraints are abundant. From regulatory and sociopolitical limitations to diminishing raw material availability, rising energy prices and the growing awareness that some waste sinks such as the atmosphere are not unlimited after all, our choices for technological systems and their components are heavily influenced and constrained by factors other than engineering or economics.[5] Although one could argue that ultimately all the constraints can be reduced to economic ones, this reductionist approach loses much of interesting and relevant detail. For example, the mechanisms through which social and raw material constraints impact on technological systems and their development can be quite different.

The literature on the history of technological systems is rife with examples of constraints affecting technological development, from how gasoline shortages altered the design of automobiles to how raw material constraints pushed jet engine designers in Second World

[4]For examples, see e.g. Gibbert, M., & Scranton, P., Constraints as sources of radical innovation? Insights from jet propulsion development; Hoegl, M., Gibbert, M., & Mazursky, D., Financial constraints in innovation projects: When is less more?; Weiss, M., Hoegl, M., & Gibbert, M., Perceptions of Material Resources in Innovation Projects: What Shapes Them and How Do They Matter?

[5]I use the term "technological system" in the sense of "open sociotechnical systems" in Hughes, T. P., Networks of Power: Electrification in Western Society, 1880–1930.

War Germany to come up with radical engine innovations.[6] Unpacking what these constraints actually mean and how they become constraints would advance our understanding of the constraints we increasingly face and truly need to overcome — and what constraints we might be able to renegotiate and reconstruct with social and rhetorical tools. These tools, in turn, are more powerful if we have analyzed and understood what makes a constraint, and how the constraints are constructed. In the end, my paper seeks to remind us that when technologists argue that their choices are constrained by certain factors, critics and historians should keep in mind that these constraints may in fact turn out to be significantly more malleable and ambiguous than the technologists themselves may acknowledge, even in confidential communications.

The story of Outokumpu's changing constraints and the development of flash smelting is also a dramatic and fascinating story in itself. It has not received much attention in the literature on the history of technology and is almost unknown in the English-speaking world. The case is also an example of rarely studied birth of an process innovation and provides a privileged view to a period of rapid change in otherwise relatively slow-moving industry. I therefore believe that the study can be useful to students of other settings and eras as well.

6.2 Background: Outokumpu and technonationalism in pre-war Finland

Finland, a country straddling the Arctic Circle and in the 1930s a home to some 3.6 million people, is not often noted in the annals of mining and metallurgy. Despite a history of small-scale mining dating to early 1500s and governmental efforts between about 1830 and 1850 to promote domestic metal sources, by the turn of the 20th century practically all mines in Finland had ceased to operate. Finland's limited and diminishing deposits could only support small-scale metallurgical industries, which were out-competed by newer methods favoring mass production. Against this background, in a country where four out of five people were employed in agriculture or forestry[7] a fortuitous 1910 discovery of a rich copper ore deposit under Outokumpu ("strange hill") in eastern Finland did

[6] For automobiles, see Hughes, T. P., American Genesis; for jet engines, Gibbert & Scranton, Constraints as sources of radical innovation?, Giffard, H. S., Making Jet Engines in World War II, and Constant, E. W., The Origins of the Turbojet Revolution.

[7] For Finnish economic history, see Hjerppe, Suomen talous 1860-1985, particularly p. 59.

not self-evidently lead to the eventual development of a major process innovation.[8]

Since the ore body had been found by employees of the government's Geological Survey, its legal ownership was initially shared between the government and the landowner. The Hackman trade house, which had purchased out other landowners in the area, did express interest in gaining total control of the deposit, but the government, realizing the importance of the discovery, adamantly refused to relinquish control to private interests before the full value of the deposit was firmly established and appropriate royalties could be determined. The question that would continue to shadow many subsequent discussions and decisions about Outokumpu for the next two decades was how the enterprise should be organized, and who should take charge. Fundamentally, the issue could be boiled down to a relatively simple question: would the wealth under Outokumpu be best exploited with the aid of foreign investors and technological expertise they could bring, or should the Finnish government seek to develop necessary expertise nearly from scratch while building up the investments required?

While the original plan had been to contract only copper recovery expertise from abroad, continuing problems with the selected recovery method and the unwieldy ownership structure led to a brief 1917-1920 interlude where Outokumpu was rented to the Norwegian developer of the method. The collapse of this venture in the aftermath of post-war slump in metal prices, Outokumpu's continuing financial difficulties and the government's desire to shut out foreign "speculators" eventually led to the mine's nationalization in 1924, with Eero Mäkinen (1886-1953) as the managing director. Mäkinen was a geology PhD with mining engineer's training and had proven his loyalty to the new Finnish state as a volunteer White Guard officer during Finland's brief but bloody civil war in 1918. He had originally been selected as state-appointed "controller" or overseer of Outokumpu in 1918, and named managing director in February 1921. After 1932, the unwieldy ownership structure was finally clarified as Finnish state-owned companies were reorganized into joint stock companies. These were to be operated outside direct political control and "according to commercial principles", even though the

[8]The overall history of Outokumpu is drawn primarily from Kuisma, M., Outokumpu 1910-1985, and Annala, V., Outokummun historia 1910-1959. For Finnish mining history, see e.g. Poutanen, P. Suomalaisen kuparin ja sinkin juurilla: Orijärven kaivos 1757-1957 (the history of Orijärvi copper mine); Nordström, W. E., Svartå Bruks Historia (the history of Svartå ironworks); histories and statistics of Finnish mining industry published by Geological Survey of Finland, particularly statistic "Finland's mines 1530-2002".

government retained practically all of the shares.[9]

Outokumpu's status as nationalized company came to play an important role in the development of flash smelting, and therefore a brief digression is in order. The clash between proponents and opponents of nationalization illustrates the different perceptions about technology, industry and the state, and the sometimes competing tensions inherent within Outokumpu and state enterprises in general. During the period, the amalgamation of interactions between engineering and nationalism had engendered a form of "techno-nationalism" [10] whose proponents competed with (generally) more conservative proponents of small state and more laissez-faire economic policies. Meanwhile, techno-nationalism allowed even staunch political conservatives such as Eero Mäkinen to find allies from the political Left, as the latter usually supported nationalization of important industries as a matter of principle. As Fridlund and Maier have noted in their work on techno-nationalism, the term "nationalism" refers here to the word's anthropological meaning of "conscious or unconscious beliefs concerning membership of a larger nation," not just the narrow political-ideological meaning.

In the end, the nationalization can be interpreted as a victory for techno-nationalistic elements within Outokumpu and Finnish government, personified in Outokumpu's managing director Eero Mäkinen, and as a defeat for laissez-faire economic policy and for those who doubted whether Finland held resources and expertise needed to run a successful mining business. Alongside many other Nordic engineers, Mäkinen undoubtedly shared the then-common notion of technological progress as a nation-building tool, particularly valuable in the still mostly agrarian and relatively poor Finland. Therefore, while economic efficiency might have suggested the mine to be rented out to foreign experts, nationalistic considerations and visions of the future required another approach.

Mäkinen's view, which he justified by his experiences during the "Norwegian period" (1917-1920), was that foreign ownership would lead to the mine being emptied rapidly and ineffectively and the ore transported elsewhere for smelting and refining. In contrast, nationalization would ensure that copper and sulfur in Outokumpu's

[9]For the history of Finnish state-owned companies, see Kuisma, M. Valtion yhtiöt: nousu ja tuho (State enterprises: their rise and fall).

[10]E.g. Fridlund, M., & Maier, H., The Second Battle of the Currents: A Comparative Study of Engineering Nationalism in German and Swedish Electric Power, 1921- 1961; Waqar, S., & Zaidi, H., The Janus-face of Techno-nationalism: Barnes Wallis and the "Strength of England", and Hecht, G., The Radiance of France. For a discussion of the mentality and values of period's Finnish engineers in particular, see Michelsen, K.-E., Viides sääty. Insinöörit suomalaisessa yhteiskunnassa; see also discussion of state-owned companies and their role in Kuisma, M., Valtion yhtiöt: nousu ja tuho.

ores would help build Finnish industry while maximizing the overall benefits to society. Furthermore, Outokumpu's ore was seen to hold strategic importance: in case of another European war, copper would be needed for cartridge cases and sulfur for paper mills, fertilizer, and the manufacture of explosives.[11]

Meanwhile, stability brought by nationalization and improving financial situation had allowed Outokumpu to proceed with its expansion plans. In 1929, the mine, whose output had been as little as 5 200 tons of copper sulfide ore in 1921, exceeded 100 000 tons of annual ore production, and in 1931, 156 000 tons were mined, yielding about 6400 tons of copper. This sufficed to put Finland on a map as an important European copper-producing country, even though Outokumpu's share of European production in 1931 was just short of 4 percent.[12] In the late 1920s and early 1930s, Outokumpu collected almost all of its revenue from exports of ore concentrate. However, Mäkinen worked hard to persuade Finnish pulp and paper mills to replace their sulfur imports with sulfur dioxide produced by treating Outokumpu's ore. Between 1932 and 1935, most Finnish pulp mills did indeed take up the offer, buttressing Outokumpu's national significance as a supplier of vital ingredient to wood and paper industries, the nationally acknowledged backbones of Finnish industrialization.[13] These interdependencies, combined with Outokumpu's financial success in the 1930s and Mäkinen's forceful promotion of growing Finnish mining and metals industry, secured Outokumpu an important position within Finnish economic life.[14]

However, turbulence due to Great Depression and the crash of copper prices put Mäkinen's grand plans temporarily on hold. From early 1920s, Mäkinen had lobbied vigorously for a domestic copper smelter and refinery. In modern terms, he wished to maximize the value added to Outokumpu's ores in Finland, as a part of his conviction that this "national treasure" should benefit Finland as much as possible. The old, inefficient copper refinery had been closed down in 1929, and planning for a new smelter, to be completed by 1933, commenced immediately. Building, however, would require funding

[11] For Mäkinen's views, see e.g. memorandum of AB Outokumpu Oy's operations at Outokumpu, E. Mäkinen 12.12.1919, folder O18 A4 1918-1925. EDA; Copy of letter draft from Eero Mäkinen to cabinet minister K. Järvinen, undated (likely April 1928), folder EM-lausunnot O26 A4 1928. EDA. Mäkinen's long-held techno-nationalism features very prevalently in e.g. his obituary by his long-time friend, professor Eskola, Eero Mäkinen: Memorial Address. For broader aspects of nationalization, see Kuisma's history of Outokumpu.

[12] Production figures from Outokumpu's annual reports in PKA. International statistics from Julihn, C. E., & Meyer, H. M. (1933). Copper. In O. E. Klessling (Ed.), Minerals Yearbook 1932-33 (pp. 27–52). All figures in metric tons.

[13] According to Hjerppe's economic history of Finland (p. 143), forest industry products comprised up to 85 percent of Finland's exports during the 1920s and 1930s.

[14] See e.g. Hjerppe, and also Kuisma's treatise on Finnish state-owned companies.

from the owner — the government. Even though the Economic Defense Council, the government body responsible for the oversight of strategic industries and materials, strongly supported the project and wanted it to proceed as rapidly as possible, the economic downturn had drained the state's coffers. Since private Finnish investors were not forthcoming, and because Mäkinen perceived the smelter to be too important to be left to foreign investors, government's refusal in 1931 left Outokumpu and Mäkinen with little choice but to shelve the project for the time being. It should be emphasized that the decision to exclude foreign investors was Mäkinen's to make. In 1932, Finnish government even suggested that the smelter should be financed with foreign loans, and a consortium of French investors offered precisely such a loan, only to be rebuffed by Mäkinen.[15]

6.3 Interlude: the technology of copper

In hindsight, the delay may have been a boon to Outokumpu. In 1929, there were two fundamentally different technologies for wresting copper from the ore. In the relatively novel hydrometallurgical method, copper could be leached from the ore using sulfuric acid and then electrolytically separated from the solution. This method had been used at Outokumpu's old refinery, but scaling and modifying it to meet the demands of increased production and the desire to separate more valuable metals from the ore presented significant challenges. For a company in a hurry, whose financial position was precarious, and which lacked technical expertise to develop novel methods, the risks of going so far beyond "entirely mature standard operating procedures" were unacceptable. As it turned out, even today hydrometallurgical methods remain problematic for copper sulfide ores of the type found at Outokumpu.[16]

The "standard procedures" Mäkinen had in mind involved smelting, that is, separating valuable metals by heating the ore. In 1929, the general consensus visible from contemporary discussions was that all these pyrometallurgical methods required plentiful external energy sources, such as fossil fuels or electricity. Of numerous different pyrometallurgical methods, Mäkinen considered seriously only the most mature one, coal-fired reverberatory smelting. To this end, he commissioned a German smelter builder Krupp-Grusonwerk for

[15] Annala, pp. 275-276.

[16] A thorough discussion of pros and cons of the various alternatives, and Mäkinen's reasons for rejecting hydrometallurgy, can be found from a memorandum "Uusi kuparitehdas, P.M. 16.12.1929" ("New copper factory"), folder EM-lausunnot O26 A4. EDA. See also a book written by Mäkinen, Vuoriteollisuus ja metallien valmistus ("Mining industry and manufacture of metals"); and other contemporary copper metallurgy manuals.

a preliminary design for a plant. However, as Finland lacked domestic fossil resources, reverberatory smelting would have been dependent on imported coal. This was a clear drawback in Mäkinen's plans, and in various memoranda he tried to soften the issue by arguing that if "war emergency" prevented coal imports, proposed copper furnaces could nevertheless be run with domestic firewood.[17] Foreign experts who reviewed the plans reinforced Mäkinen's case: under the circumstances, reverberatory smelting was "undoubtedly the correct method".[18]

Interestingly, just some years before Mäkinen had argued the exact opposite. In a memorandum from 1925, he had flatly stated that the dependence on coal meant that "the use of reverberatory furnace cannot be contemplated [in Finland]."[19] The principal reason for this flip-flopping was a change in the expectations of technological feasibility, brought about largely by nationalistic considerations. The 1925 plans stipulated a small operation where limited quantities of copper would be extracted with previously used hydrometallurgical methods without resorting to smelting at all. In contrast, the 1929 plans sought to expand production with a significantly larger plant that could also recover other metals, particularly strategically important iron, as byproducts. This would not be possible with hydrometallurgy.

However, there were no purely commercial reasons that necessitated a smelter of any kind. Outokumpu could well have operated a small-scale copper extraction business for meeting a part of domestic consumption while exporting most of its copper ore concentrate, or even concentrate on very profitable ore exports only, but in 1929, these no longer fit Mäkinen's vision of Outokumpu as a linchpin of Finnish metals and chemicals industry. If the Great Depression hadn't intervened, it seems very likely that Mäkinen would have obtained the funding and proceeded with reverberatory smelting. As it happened, the delay allowed Mäkinen some time to think about the alternatives.

Surviving records and extant histories do not tell precisely when Mäkinen began to question the commitment to reverberatory smelting, but soon after government's negative funding decision he asked Finnish engineer K.E. Ahola, who was pursuing his PhD studies in

[17] Aside from aforementioned 1929 memorandum, this argument is made again in two separate memoranda addressed to government's Economic Defense Council, dated 5.2.1930 and 21.3.1930. Folder EM-lausunnot O26 A4. EDA.

[18] The quote and details of Krupp-Grusonwerk's plans are from two external reviews by consulting engineers Palén and Münker. In folder Uusi kuparitehdas 1929-1933. EDA.

[19] Memorandum by Mäkinen, "Muistio Outokummusta 13.2.1925." See also memorandum "Outokummun kehityksestä ja sen tuotannon lisäämisestä," dated 25.10.1923 (Of Outokumpu's development and increasing its production). Folder O18 A4 1918-1925. EDA

Germany with a stipend from Outokumpu, to study the possibility for smelting Outokumpu's ore with electricity.[20] Electric smelting had been practiced since late 1800s in some rare locales endowed with plentiful hydropower reserves.[21] As Mäkinen and Ahola saw it, the method offered certain benefits over reverberatory smelting, including better control over metallurgy and pollution and possibly more economical operation, provided that electricity could be obtained cheaply enough. Since 1921, a potential source of such power had been under construction at Imatra, near the Soviet border and close to the preferred location for the smelter. Its first three turbines were completed in 1929, but even though the timeline would have fitted Outokumpu's preferred schedule, there is no evidence of electric smelting being even considered for Outokumpu before 1931.[22]

Nonetheless, further investigations resulted to a switch in preferred furnace technology. Electric smelting could be cheaper, and it eliminated the main drawback of the previous plan, its dependence on coal imports. In May 1933, Outokumpu unveiled a plan to build an electric smelter if state-owned utility Imatran Voima would sell its electricity cheaply enough. Otherwise, the earlier plan calling for coal-fired reverberatory furnaces would stand.[23] Negotiations concluded successfully in January 1934, however, and what was at the time the world's largest electric copper smelter was finally inaugurated in February 1936. Once the planned copper refinery and copper mill were completed in 1941, Finland was self-sufficient in copper products and gained a strategic resource that was particularly valuable during the barter and quid pro quo trade of the war years. The exact value of Outokumpu's products during the war years is hard to ascertain due to the nature of the trade, but it is clear that they were of considerable importance.[24]

6.4 The war years and after: the birth of flash smelting

The outbreak of the Second World War seemed to vindicate the misgivings about coal as a fuel. Availability of fossil fuels in Finland diminished considerably due to supply disruptions, and by 1945 total

[20] Letter from Mäkinen, dated 8.10.1931, and Ahola's response. Correspondence between Mäkinen and K.E. Ahola, 5.1. — 21.12.1931. Folder Kirjeenvaihto 1931 A-Ki, K31. OKA.

[21] Lyon, D. and Keeney, R. The Smelting of Copper Ores in the Electric Furnace.

[22] Heikinheimo, M. (Ed.) Sähkö ja sen käyttö. (Electricity and its uses.)

[23] "Estimates of Costs of Construction and Production for Outokumpu Copper Smelter", memorandum dated May 29th 1933. Folder Imatran kuparitehdas 1933-1938. MÄK.

[24] See e.g. Vuorisjärvi, E. Petsamon nikkeli kansainvälisessä politiikassa 1939-1944; Perkins, J. Coins for Conflict: Nickel and the Axis, 1933-1945.

fossil fuel use had fallen to approximately one quarter of pre-war levels.[25] On the other hand, mobilization greatly reduced demand from civilian economy, and a 25 percent increase in firewood fellings was able to compensate the lack of fossil fuels to some extent. Still, Eero Mäkinen and the Economic Defense Council must have been relieved that Outokumpu's ore was being smelted without imported fuels and could contribute to Finland's all-out mobilization. While hard evidence remains scant, it seems reasonable to believe that wartime experiences - including the death of his son in action in 1942 - only served to strengthen Mäkinen's already well-developed techno-nationalist leanings.

While the fuel choice had been undoubtedly correct from wartime perspective, in retrospect the Soviet border had not been the best location for an important national asset. The smelter nevertheless continued to operate until summer 1944, when a Soviet offensive forced it to evacuate to Harjavalta, at western coast of Finland. The smelter was disassembled and moved to a new site, resulting to six-month halt in production. Even worse, armistice in September resulted to the Soviet Union annexing large tracts of Finnish land, including two major hydropower plants. At a stroke, approximately one third of Finland's pre-war electricity generation capacity was lost. For Outokumpu, the shortage was compounded by location: compared to Imatra, where another state-owned company produced vast amounts of cheap hydropower, at Harjavalta the electricity had to be obtained from sometimes recalcitrant private companies. In western Finland, the electricity grid was built and operated largely by private pulp and paper producers, and their requirements could be at odds with the newcomers' demands.[26]

This move from a state-centered technological regime, to use Hecht's concept of technological regimes, to a privately operated regime combined to drive up the price of electricity for Outokumpu.[27] The average (inflation corrected) price more than doubled from 1944 to 1945 and continued to rise, reaching a peak at nearly eight times the 1944 prices in 1948. As a share of total costs per ton of copper, the cost of electricity went from less than ten percent to 40 percent in 1948.[28]

[25] Statistics Finland. The use and sources of energy 1917–2007.

[26] Tensions are illustrated in e.g. correspondence between Mäkinen and local electricity utility chief G.M. Nordensvan. Folder Kirjeenvaihto 1945 H-Ö, K31. PKA. I thank an anonymous reviewer for pointing out the tensions Outokumpu's move to a privately owned electricity grid may have engendered.

[27] Hecht, Radiance of France. For a study of technological regimes in Finland, albeit in different context, see Särkikoski, Rauhan atomi, sodan koodi. I'm again indebted to anonymous reviewer for pointing out the connection.

[28] Electricity prices and costs from Outokumpu annual reports. Folder Vuosikertomuksia,

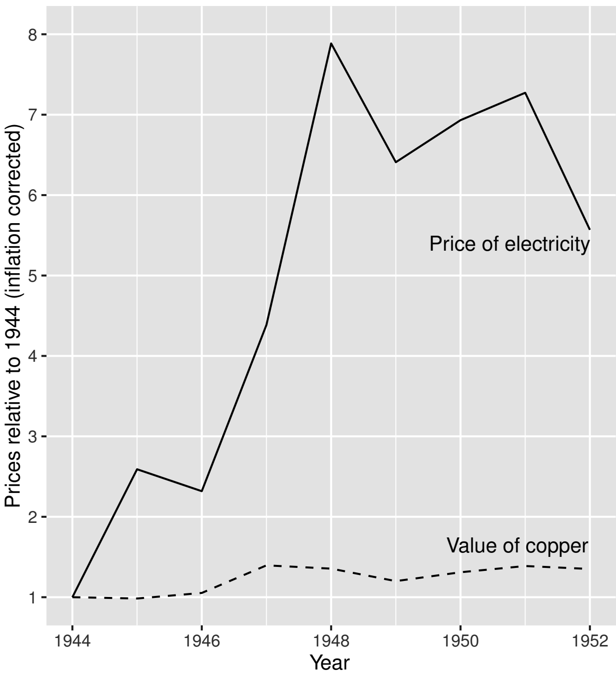

Figure 6.1: Relative prices of electricity and copper in post-war Finland. Inflation-adjusted relative price of electricity, and relative price of copper in the U.S. (in constant 1998 dollars, to illustrate the approximate value of Outokumpu's production.) It should be emphasized that war reparation quotas and export license system meant that the value of Outokumpu's production and its importance to post-war Finnish economy cannot be reliably assessed by average market price alone. Electricity prices and costs from Outokumpu annual reports. Folder Vuosikertomuksia, E1. PKA. Copper prices from Kelly, T. D. and Matos, G. R., Historical Statistics for Mineral and Material Commodities in the United States.

As the year 1944 was drawing to close and even before the electric smelter was operational at Harjavalta, Eero Mäkinen therefore penned the letter mentioned in the introduction, calling for his engineers to develop an alternative to electric smelting. In the letter, he briefly noted that while industry standard reverberatory furnace might seem to be the straightforward choice, its coal would have to be imported. Therefore, his engineers would have to come up with a furnace that wouldn't need either fuels nor electricity to smelt copper concentrates. Mäkinen had more or less made up his mind, and in all surviving communications, other possibilities merited only two

E1. PKA. Copper prices from Kelly, T. D. and Matos, G. R., Historical Statistics for Mineral and Material Commodities in the United States.

very brief mentions.[29],[30]

On the face of it, Mäkinen's dismissal of reverberatory smelting and his call to go beyond state of the art is puzzling. The times were bad for experimentation, as Outokumpu's products were now needed more than ever. In addition to rebuilding the war-ravaged country and earning invaluable foreign currency, copper products featured heavily in the onerous war reparations the Soviet Union demanded as a price of not occupying the country. Signed two weeks before Mäkinen's letter, on 17th December 1944, the war reparations agreement called for a delivery of 300 million pre-war dollars' worth of specific industrial goods (e.g. cables, locomotives, ships, electric and industrial machinery) in six years. Relative to size of economy, the reparations exceeded those demanded from Germany in 1919.

The brunt of the demands was placed on products of metals industries. Outokumpu's copper was a critical ingredient in many products, and full 90 percent of its planned 1945 output was allocated for the war reparations products. deliveries. These deliveries consumed the majority of smelter's output until 1948. As one contemporary observer put it, the demands were "frightfully large".[31] Furthermore, Outokumpu's byproducts (sulfur and iron) were in demand in other sectors of Finnish economy.[32] By the time he wrote his letter, the broad lines of the war reparations demands must have been known to Mäkinen, who was active in politics as well. In fact, he was so well-connected that he would be elected into Finnish parliament as a member of conservative Coalition party in April 1945 and before his unexpected death in October 1953 he served briefly as a cabinet minister of public works.

An unstated but prevalent fear among many Finns at the time was that any delays in reparations deliveries could and would be used by the Soviet Union as a pretext for Communist takeover or even Soviet occupation and annexation. Furthermore, copper was scarce in Europe: if Outokumpu did not deliver, copper might have been impossible to obtain at any price. In this light, Outokumpu would have been perfectly justified to continue using its proven electric furnace or to switch to another proven process instead of employing

[29] "Electricity demand of Harjavalta copper smelter," letter to engineering consultancy Ekono, charged with implementing energy rationing measures, 23.12.1944.

[30] Letter from Mäkinen to local electricity utility chief G.M. Nordensvan, 6.10.1945. Folder Kirjeenvaihto 1945 H-Ö, K31. PKA.

[31] Heikkinen, S. Sotakorvaukset ja Suomen kansantalous (War reparations and the Finnish economy), p. 100. Also Michelsen, K-E. Sotakorvaukset: Suuren teollisen projektin anatomia (War reparations: the anatomy of a grand industrial project), quote from p. 209. Both in Rautkallio, H. (ed.), Suomen sotakorvaukset (Finnish war reparations). For Outokumpu's role, see Kuisma, M., Outokumpu 1910-1985, p. 235 onwards.

[32] See e.g. Rautkallio, H. (ed.), Suomen sotakorvaukset (Finnish war reparations).

its valuable engineering staff and spending its reserves of spare parts on what could well have been a wild goose chase. In particular, fireproof furnace bricks were in a very limited supply: A December 1944 letter in Outokumpu's archives despairs that furnace bricks simply cannot be found in Finland or imported from war-torn Europe.[33]

Against this background, the demands these more conservative options placed on Finnish energy resources would almost certainly have been manageable. First, while electricity shortage was real, Finnish industries managed to cope. When the crisis reached its peak after a dry spell had drained hydropower reservoirs in 1947 and electricity was finally rationed, nationally important industries were at the top of the list of consumers still receiving electricity.[34] Although supply situation did cause some headaches for Finland's two electric smelters — the another being Vuoksenniska steel works, also built to exploit Imatra's hydropower but not evacuated during the war — there are no indications of deliveries being endangered because of insufficient supply. A thorough examination of Vuoksenniska's archives surviving at Central Archives for Finnish Business Records (ELKA), while uncovering plenty of correspondence about rationing, failed to unearth any evidence of significant disruptions. Furthermore, Vuoksenniska even increased its electricity use during the period.

In fact, even Outokumpu coped with the worst electricity shortage in Finnish history: flash smelting became operational only in 1949, after electricity rationing was already over, and even as late as in 1953 electric smelting accounted for nearly a third of total production.[35] Outokumpu did consider a partnership with a local paper mill in order to build a new hydropower station as an alternative to flash smelting, but the success of the latter made this plan ultimately redundant.[36]

Second, even if Outokumpu had switched to coal-fired reverberatory smelting, the increase in coal demand would hardly have been overwhelming. In a letter written exactly one week before aforementioned 1944 letter to his engineers, Mäkinen informed Ekono, a consulting organization responsible for energy rationing measures, that Outokumpu was prepared to convert to coal-fired reverberatory smelting should electricity supply be in jeopardy.[37] At this time, the

[33] Letter from Kymi Ltd., 20.12.1944. Folder Kirjeenvaihto 1944 A-U, K31. OKA. See also Särkikoski, T. Flash of Knowledge.

[34] Principles of rationing were established in circular N:o 23848 from Kansanhuoltoministeriö (Ministry of Supply) to grid-connected electric plants, received at Outokumpu on 3.10.1947. Folder Kirjeenvaihto 1947 A-Ke, K31. PKA.

[35] Kuisma, M. Outokumpu 1910-1985, p. 126.

[36] Kuisma, Outokumpu 1910-1985, p. 166.

[37] "Electricity demand of Harjavalta copper smelter," letter to engineering consultancy

coal situation in Finland was as dire as it would get during these years. In late September, coal and coke reserves totaled 345 000 metric tons, a far cry from estimated annual demand of 850 000 tons.[38] However, Mäkinen's letter to Ekono stated that if Outokumpu were to fully replace electric smelting, it would need only 18 000 tons of coal per year; less, if some electricity could be obtained as well. As a bonus, waste heat from the furnace would be used to generate electricity, easing demands elsewhere. It is worth noting that Mäkinen's letter contained no indications that Outokumpu had to abandon electric smelting. Furthermore, coal supply situation began to improve fairly soon during 1945, well before Outokumpu made a firm decision to build a flash furnace.

Third, there is no evidence whatsoever that Mäkinen and Outokumpu even seriously considered using firewood to replace or supplement electricity or other fuels. In early 1930s, Mäkinen himself had justified the reverberatory plans by arguing that firewood would be used as an alternative fuel if coal supplies were in jeopardy. Firewood had been used extensively to supplement fuel imports in wartime Finland, and consumption peaked at 25 million cubic meters in 1945.[39] According to figures presented in a 1925 study about relative merits of coal and firewood in Finland, the 18 000 tons of coal could have been replaced completely with 90 000 to 120 000 cubic meters of firewood, depending on its quality.[40] If some coal or some electricity could have been obtained, the demand would have been correspondingly lower. This would have represented a sizable but hardly impossible increase in firewood demand, particularly as the demobilization of the army freed thousands of able-bodied men to seek employment in the forestry sector.

All in all, given the importance of Outokumpu's copper and byproducts, it is hard to believe that forceful Eero Mäkinen wouldn't have been able to browbeat the government into allocating electricity, coal import quotas, firewood or some combination of the above to Outokumpu, even if that had meant more stringent rationing among the populace. In other, arguably less pressing issues ranging from spare parts to miners' rations, Mäkinen and Outokumpu's management had not hesitated to leverage Outokumpu's importance to war reparations and to national economy when demanding pref-

Ekono, charged with implementing energy rationing measures, 23.12.1944.

[38] Seppinen, J. Vaaran vuodet? Suomen selviytymisstrategia 1944-1950, particularly p. 155 onwards.

[39] Statistics Finland. The use and sources of energy 1917–2007.

[40] In Voima- ja Polttoainetaloudellinen yhdistys Ekono, publication N:o 10: Kivihiili höyrykattilan polttoaineena (Coal as a fuel for steam boiler).

erential treatment.[41] Copper must flow for Finland's sake, Outokumpu's management argued when demanding new conveyor belts or more tobacco for the miners. But in the critical furnace issue, Mäkinen apparently did not even attempt to exert his considerable influence. Why?

We need to seek the reason for his behavior from another change in the perceptions of what was technologically feasible and desirable. In 1944, Outokumpu was a different company to what it had been in 1929 or even in 1939. Rather than being a newcomer to metallurgy in a country with scant traditions in metals industry, during the last decade it had built and operated advanced, large-scale metallurgical plants, building a considerable experience base. Perhaps most importantly, Mäkinen's long-standing efforts to buy, license, or steal necessary foreign technologies and expertise in order to nurture domestic engineering expertise had borne fruit. In the international copper industry, much of the information and knowledge were shared relatively freely even among potential competitors; for example, in 1949 the chief developer of a competing method was given a tour of Harjavalta smelter.[42] However, oral tradition holds that Outokumpu was not above resorting to industrial espionage when necessary, and some of the passages in abovementioned early 1930s correspondence between Mäkinen and K.E. Ahola are certainly suggestive.

In any case, Outokumpu's plants were using state of the art technologies, and they were finally staffed with capable home-grown engineers. Outokumpu did not have a research and development department per se, and before 1949, its small laboratory focused almost exclusively on quality control. However, solving problems inherent in running metallurgical processes and coping with wartime exigencies had honed its engineers' skills and confidence in developing and scaling up novel solutions to unexpected problems.[43] The company's rising star and later managing director Petri Bryk (1913-1977) in particular had played an important role in these exploits, including developing a domestic method for extracting valuable nickel from Finnish ores (an invention that resulted to Outokumpu's first in-house patent in 1942), and as he would later explain, after these successes and the considerable experience with "elegant" electric

[41] See e.g. the correspondence between Outokumpu and Suomen Gummitehdas Ltd. regarding spare parts (April 1945, in folder Kirjeenvaihto 1945 C-G. PKA) and 1947 efforts to attract more miners with extra rations (letter to Minister of Supply Murto, 22.7.1947. Folder Kirjeenvaihto 1947 A-Ke, K31. PKA).

[42] Letter from Paul Queneau (Inco), 10.8.1949. Folder Liekkisulatus — tiedusteluja. TJA.

[43] See the history of Outokumpu's metallurgical research, Mäntymäki, H. "Fugit Irraparabile Tempus".

smelting "it felt uncomfortable to take a step backwards in smelting technology."[44] In this way as well, confidence made flash smelting more attractive than "backwards" alternatives. Bryk's words and the overall attitude of Outokumpu's engineers are a reminder of how technical criteria alone can only rarely explain technologists' support for new technologies.[45] Nevertheless, this case illustrates how enthusiasm needs to be backed by confidence in the new technology.

6.5 The problem that had "very much vexed the minds of professional men:" the development of flash smelting

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This confidence enabled Mäkinen and Outokumpu to pursue solutions that had been far from maturity in early 1930s. In itself, the idea of smelting copper ore using only energy from the ore itself (so-called "autogenous" smelting) was not a novel one for any competent copper metallurgist in the world in 1944. Sulfur could burn and release energy, and in a different form, the idea had been utilized in the industry between approximately 1890 and 1935. Finnish metallurgists were perfectly aware of this "pyritic" method and its variations, as evidenced by a detailed discussion in a textbook of mining and metallurgy written by Eero Mäkinen himself in 1933.[47] However, this early method was a dead end because it required a rare type of ore.[48] Once suitable deposits were exhausted, the method fell into disuse. Nevertheless, the idea continued to attract metallurgists who were always on a lookout for cost savings, as the fuel savings and general simplification of the smelting process could theoretically halve the smelting costs.[49]

Meanwhile, ore concentration technology had developed as a response to falling copper ore grades, and in the 1890s, prototypes of these concentrators began to produce extremely fine, almost powder-like copper sulfite concentrate. In this form, sulfur was in theory

[44] See e.g. Mäntymäki, H. "Fugit Irraparabile Tempus"; Särkikoski, Petri Bryk. Quote from Petri Bryk's presentation on flash smelting at Harjavalta, 27.3.1949. Folder Autogen etc. TJA.

[45] Schatzberg, E. Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920-1945; Schatzberg, E. Wings of Wood, Wings of Metal: Culture and Technical Choice in American Airplane Materials, 1914-1945.

[46] Title quoted from Bryk's 27.3.1949 presentation.

[47] Mäkinen, E., Vuoriteollisuus ja metallien valmistus, pp. 452-454 in particular.

[48] Sticht, R., Pyritic Smelting — Its History, Principles, Scope, Apparatus, And Practical Results.

[49] Sticht, R. Pyritic Smelting.

much easier to ignite than it had been in earlier, gravel-like concentrates, and the first known patent for a furnace burning pulverized concentrate dates from 1897.[50] The essential components of Outokumpu's eventual furnace design were already included in a 1915 patent, and other inventors continued to tinker with the design up until the war. [51] In the 1930s, active research and development efforts were conducted in the United States, Canada, France, Yugoslavia, and Soviet Union.[52] Despite some promising initial results, these experiments did not lead to operational furnaces. In particular, the slump in raw material prices caused by the Great Depression had made copper producers reluctant to invest in new, uncertain technologies.

Nevertheless, contemporary observers clearly believed that the autogenous method held promise. As two of them noted in a treatise on copper metallurgy published in 1942, by then the necessary components and know-how seemed to be available and the only remaining obstacle was the construction of a suitable furnace.[53] Development resumed after the war, and Canadian mining giant Inco actually beat Outokumpu by a few months with its own pilot furnace using the same idea but quite different principles. Inco's furnaces maintained critical heat balance by enriching air with oxygen (and therefore avoided heat loss from heating nonreactive nitrogen in normal air), while Outokumpu recycled waste heat with heat exchangers. When these proved unmaintainable, Outokumpu compensated with fuel oil burners. Problems with oxygen generators caused Inco's commercial scale furnace to be delayed until 1952. Nevertheless, the Inco furnace was even more efficient than Outokumpu's, so much so that Inco, unlike Outokumpu, refused to license its design to potential competitors. There are no indications, however, that Inco's post-war work had any direct influence for Outokumpu's research and development.[54]

[50] Bridgman, H. L.,U.S. Patent 578,912: Process of Reducing Ores.

[51] Klepinger, J. H., Krejci, M. W., & Kuzell, C. R., U.S. Patent 1,164,653: Process of Smelting Ores. Of examples of later inventors, see e.g. Freeman, H., U.S. Patent 1,888,164: Process of Smelting Finely Divided Sulphide Ores; Zeisberg, F. C., U.S. Patent 2,086,201: Ore Roasting; Haglund, T. R., U.S. Patent 2,209,331: Roasting Process.

[52] Cooper, J. P., & Laist, F., An experimental combination of shaft roasting and reverberatory smelting. Norman, T. E., Autogenous Smelting of Copper Concentrates with Oxygen-enriched Air. Bouthrou, J., "Saint-Jacques-ugnens användning för behandling av floterade kopparsalsskoncentrat." (The use of Saint-Jacques furnace for copper flotation concentrates.) 17.7.1937. Folder Liekkisulatus 1945-54. BRY. See also Bryk et al., Flash Smelting Copper Concentrates; and an undated note listing Russian language articles in Outokumpu's library about autogenous smelting from 1934 to 1945, in folder Kuparirik. sulatuksesta Venäjällä, TJA.

[53] Newton, J., & Wilson, C. L., Metallurgy of Copper. Pp. 160-161.

[54] For a comparative study of the two, see Korhonen, J. M., & Välikangas, L., Constraints and Ingenuity: The Case of Outokumpu and the Development of Flash Smelting in the Copper

Under Mäkinen, Outokumpu had assiduously cultivated its knowledge base and international contacts. As a result, Outokumpu's experts were certainly aware of developments in the field, as insider reports from Yugoslavian experiments in its archives can confirm.[55] In fact, Krupp-Grusonwerk, Outokumpu's original choice of furnace supplier, had suggested a very similar autogenous furnace for Outokumpu already in the early 1930s, but "the deal fell through because the furnace was then much too experimental."[56]

But in 1944, Mäkinen was confident enough of two things: first, flash smelting was in a technical sense a feasible proposition; and second, that his staff could and should make it work. As noted above, the components were known to exist, Outokumpu's staff was competent enough, and now the question was simply how to put the pieces together. Whether the furnace would prove to be economical was another matter entirely. No evidence survives of detailed cost calculations from that period. However, assessing the overall desirability of flash furnace in 1944 would in any case have been extremely difficult, because rationed supply and war reparations demands meant that normal economic calculations did not necessarily apply. In 1951, after the worst was already over, the costs of electric and flash smelting were determined to be almost exactly the same when ongoing R&D costs — in 1947, representing 12 percent of Outokumpu's annual revenues — were included.[57] Nonetheless, in Outokumpu's techno-nationalistic atmosphere, the flash furnace was an attractive proposition simply because it could help Finland in her energy crisis.

Mäkinen's belief in the technical feasibility and desirability of a furnace independent from external fuel sources, and his nationalistic motivations, influenced how Outokumpu's staff again perceived the coal constraint. As in 1925, so in 1945: "[T]he use of reverberatory furnace cannot be contemplated here, as we do not have cheap oil or coal that this method absolutely requires," Mäkinen had written in 1925.[58] "[R]everberatory smelting was intolerable because the whole copper production would have become dependent on fuel imports from abroad," wrote Bryk in an English introduction to flash smelting in late 1951.[59] Bryk, who was being groomed to succeed

Industry

[55]Bouthrou, Saint-Jacques...

[56]Mäkinen's letter on 30.12.1944.

[57]Memorandum on production costs of copper, 12.1.1952. Folder Liekkisulatus 1945-54. BRY. See also Memorandum "Flash smelting - electric smelting." 27.9.1954. Folder Liekkisulatus 1945-54. BRY. Kuisma, Outokumpu 1910-1985, p. 126.

[58]"E. Mäkinen. Muistio Outokummusta 13.2.1925." Folder O18 A4 1918–1925. EDA

[59]"Autogenous flash smelting at the Harjavalta Copper Smelter of Outokumpu Oy. P.B. 28.12.1951." Folder Autogen etc. TJA.

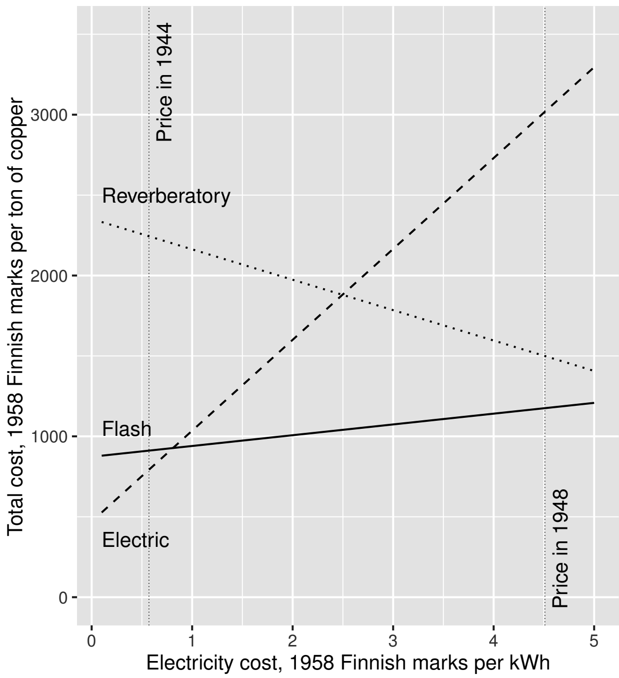

Figure 6.2: Total cost per ton of copper in 1958 as a function of electricity price with flash, electric, and fuel-oil fired reverberatory furnaces. R&D costs are not included. By that time, cheap and easily handled fuel oil (even scarcer than coal in 1944) had replaced coal in many copper smelters, and the calculation does not fully represent the situation in 1944. From "Comparison of Smelting Costs for Different Smelting Methods". 26.3.1958. Folder Liekkisulatuslaskelmia. TJA.

ailing Mäkinen, had internalized the techno-nationalist frame that made coal imports such an "intolerable" problem — fittingly enough for a man who would become the managing director of state-owned Outokumpu after Mäkinen's death in 1953 and remain at the post until 1972.

6.5.1 Conclusions

The history of Outokumpu's development of flash smelting should serve as a reminder that perceptions of technological constraints and even shortages of important inputs or raw materials may be just that — perceptions. There is no denying that wartime supply problems and post-war electricity shortage did motivate Outokumpu to seek alternatives to electric smelting. Absent the post-war shortage of electricity in Finland, it seems unlikely that Outokumpu would have developed flash smelting. (Interestingly, in neighboring Sweden, an important Boliden copper works concluded in late 1940s that wartime supply shortages were reason enough to convert its smelter from coal-fired reverberatory to electric furnaces to prevent future disruptions.[60]) However, the electricity shortage in itself did not determine how Outokumpu responded to it. As I've tried to illustrate, Outokumpu had a menu of at least three other options at its disposal, and given the politico-economic situation, could hardly have been faulted had it resorted to any of these instead. History could well have turned out differently, and if Outokumpu's engineers hadn't managed to make flash smelting work, Outokumpu and Eero Mäkinen might be remembered not as bold innovators but as gamblers who could not resist squandering resources on a fool's errand even when the independence of Finland might have been at stake. After all, the development of flash furnace was not without difficulties: as late as in 1954 Harjavalta's employees were concerned enough about their jobs that they delivered a widely signed petition listing eleven serious concerns they had about the technical and economic viability of flash smelting.[61]

However, evidence suggests that Outokumpu's management and most importantly Eero Mäkinen strongly believed they could and should make flash smelting work. Their belief in the feasibility of flash smelting was grounded on their knowledge about the experiments and theoretical assessments from the previous five decades, and on Outokumpu's demonstrated ingenuity during the war. Nevertheless, investing in flash smelting's development must have been a risky venture for Outokumpu. As a result, Mäkinen's techno-nationalistic beliefs played a crucial role: Outokumpu would take the risk because it was a right thing to do. In brief, the reason why Outokumpu abstained from resorting to other alternatives can be best explained by Outokumpu's perceptions of feasibility and desirability of an alternative that did not require either electricity or coal. If Mäkinen and his key aides hadn't believed that flash smelting was both feasible and desirable, it seems more than likely that Outokumpu would have done what other Finnish industries at the time did — and pressured the government for coal or electricity.

This line of reasoning and evidence suggests that the coal and electricity constraints Outokumpu's management lamented and subsequent histories have implicitly accepted as immutable external forces were, to a large extent, intermingled with socially constructed

[60]Herneryd, O., Sundström, O. A., & Norra, A. Copper Smelting in Boliden's Rönnskär Works Described.

[61]Memorandum "Harjavallan kuparitehtaan sulatusuunin toiminta," in folder Liekkisulatus 1945-54. BRY.

obstacles. Constraints arise from perceptions of feasibility and desirability, and are as much a reflection of what was believed possible as what was thought to be impossible. An understanding of constraints was shared among Outokumpu's technologists, constituting a shared technological frame that guided decision-making and was perpetuated by the decisions made.[62] Once electric smelting was chosen, for example, attempts to change the technology would have to contend with the perception (true or false) that coal constraint had caused the selection of electric smelting, and therefore alternatives should also avoid using coal if at all possible.

This is not to say that constraints were imaginary. Lack of coal seams in Finland, for instance, was something that affected the decisions made by Finnish industries, and fundamental physical realities determine how much energy is at minimum required to break copper ore to its constituent elements. However, constraints can be subject to significant redefinitions when perceptions of technological feasibility or desirability demand it. Outokumpu's relationship with coal illustrates such reversals nicely. Dependence on coal made reverberatory smelting completely unacceptable to Eero Mäkinen in 1925. Only four years later, no other technology could be even considered and coal supplies were no problem at all, as Mäkinen's perception of the scale of copper industry desirable for Outokumpu and Finland had changed. Finally, after the decision to build the electric smelter in 1933, dependence from coal was again a reason, among others, to reject any thoughts of reverberatory furnaces.

The case study presented here shows how research can benefit from problematizing the concept of constraints instead of taking them as exogenous factors beyond the influence of technologists. Technologists and their beliefs about what is "good" have significant influence on what they believe to be feasible or infeasible. This finding echoes Schatzberg's now classic analysis of how ideology of metal as a symbol of progress is required to explain aviation community's enthusiasm towards metal instead of wood construction during the interwar period.[63] As an addition to Schatzberg's findings, I might suggest that perceptions of feasibility (or infeasibility) have a significant influence as well.

My study also casts further doubt on the more deterministic readings of technological change: even when confidential, presumably

[62] See the literature on technological frames, e.g. Bijker et al., The Social Construction of Technological Systems, and Bijker, W. E., Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change. See also Orlikowski and Gash, Technological Frames.

[63] Schatzberg, E. Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920-1945; Schatzberg, E. Wings of Wood, Wings of Metal: Culture and Technical Choice in American Airplane Materials, 1914-1945.

frank communications from technologists describe something as a constraint, it is possible that relatively small changes in the perceptions of technological feasibility or desirability can greatly alter the technologists' opinions of constraints. Researchers should therefore pay careful attention to the assumptions behind any statements that declare a particular path as impossible. As Mäkinen's flip-flopping between 1925 and 1929 illustrates, when one assumption — in this case, plant size — is altered, the seemingly intolerable constraint may suddenly become perfectly tolerable. Such reversals serve to underscore the importance of questioning and criticizing past and present narratives that suggest lack of alternatives for a decided course of (technological) action. Alternatives may, in fact, be even more straightforward than the ultimately decided course of action, but as this brief history shows, they are often forgotten afterwards. Historical research that can access contemporary deliberations should therefore serve as an useful antidote against excessive determinism.

6.6 Acknowledgments and author bio

Janne M. Korhonen is a PhD candidate at Aalto University School of Business in Helsinki, where he is specializing on how perceived constraints influence technological change and technological change influences perceived constraints. He wishes to express his gratitude to Markku Kuisma and Tuomo Särkikoski, whose prior research on Outokumpu helped greatly in locating many key documents mentioned in this paper. Furthermore, he would like to thank the editor, the Technology and Culture referees and the participants of Science and Technology Studies seminar at the University of Tampere for their valuable comments on earlier versions of this article. The research presented here wouldn't have been possible without a generous grant from Jenny and Antti Wihuri Foundation.

6.7 Bibliography

6.7.1 Archival and Oral Sources

The key sources for this paper have been the archives of Outokumpu Ltd. and its predecessors at the Central Archives for Finnish Business Records (ELKA) Mikkeli, Finland. These have been supplemented by 58 books on copper mining and metallurgy from 1848 to 1976, the contemporary trade and scientific press, and official histories of Outokumpu and flash smelting mentioned in the text. A full list of books consulted is included as an Appendix of this thesis.

The abbreviations in parenthesis refer to specific collections of Outokumpu archives as follows:

–, (PKA): Pääkonttori (Main Office) papers

–, (OKA): Outokummun kaivos (Outokumpu mine) papers

–, (MÄK): Eero Mäkisen arkisto (Eero Mäkinen's archive)

–, (BRY): Petri Brykin arkisto (Petri Bryk's archive)

–, (TJA): Toimitusjohtajan huonearkisto (Managing Director's personal archive)

–, (EDA): Edeltäjien arkistot (Archives of Outokumpu Oy's predecessors)

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Chapter 7

Essay IV: Overcoming scarcities through innovation

What do technologists do when faced with constraints?

The question that still divides many debates about sustainability is the possibility of technological substitution of scarce natural resources. While there is considerable debate among economists whether technology can mitigate scarcities through development of substitutes, there is little actual research on the mechanisms and limitations of this substitution process. In this study, I seek to build a bridge between scarcity and innovation literatures to study when technologists decide to develop technological substitutes. My starting point is the theory of technology as a recombination of existing mental and physical components. Combining this theory with modern scarcity literature that differentiates between absolute, relative, and quasi-scarcities yields a more nuanced framework for understanding both different types of scarcities, and how technologists decide whether or not to develop or adopt technological substitutes. This improves our understanding of the possibilities — and limitations — of scarcity-induced innovation. I then illustrate the use of this framework with two brief historical case studies about constraint-induced innovation. I conclude that the mainstream economic practice of assuming that substitution will occur automatically, even in cases of absolute scarcity, may hide extremely important phenomena from discussion and debate behind a veil of circular reasoning.[1].

7.1 Introduction

An old maxim announces that necessity is the mother of invention. If so, shouldn't humanity rest easy, knowing that technological progress will ultimately overcome whatever environmental and other problems the future may bring? Even though debates between proponents of human ingenuity and its skeptics have raged at least since the famous bet between pessimist Paul Ehrlich and optimist Julian Simon (Sabin, 2013), the question itself is surprisingly underresearched. While the Simon/Ehrlich bet was ultimately decided in Simon's favor and many believe the flexibility of market economy can at least in principle mitigate any scarcity, critics have justly pointed out that there are no guarantees human ingenuity and flexible markets will always be able to overcome all obstacles.

Generally, however, the belief in the human ingenuity remains strong. Those who question the possibilities of technological development to mitigate environmental and social ills are often derided as "malthusians" or "luddites," since so far our economy has been fairly resilient despite warnings of imminent scarcities. The "Porter hypothesis" (Porter and van der Linde, 1995c) and related research (for an overview, see e.g. Ambec et al., 2011) goes even one step further and argues that scarcities are not just obstacles to be overcome: instead, increasing scarcities such as those put in place by strong (environmental) regulation may even accelerate economic development, as they force companies to develop new technologies. However, quantitative evidence suggests that regulatory scarcities so far have had little effect on the rate of overall innovation (e.g. Newell et al., 1999; Roediger-Schluga, 2004). Nevertheless, even less sanguine observers generally believe that environmental challenges can be mitigated through technological change. Even if scarcities do not accelerate innovation as such, new technologies are believed to eventually replace legacy "dirty" technologies if sufficiently strong inducements, such as regulatory push and pull, exist (e.g. Horbach et al., 2012). This view is implicitly based on dominant neo-classical economic thought, where resource scarcities are eventually solved through substitution triggered by rising resource costs.

Increasingly, critics of mainstream economic thought[2] have ex-

[1] This essay has been published as Korhonen, J. M. (2018). Overcoming scarcities through innovation: What do technologists do when faced with constraints? *Ecological Economics*, 145, 115-125.

[2] I use the term "economic thought" to separate research on economics from economics-

pressed alarm that this formulation may not adequately cover the phenomenon of scarcity (Bretschger, 2005; Baumgärtner et al., 2006; Daoud, 2011, 2007; Raiklin and Uyar, 1996; Sahu and Nayak, 1994). These scholars argue that mainstream economics limits itself to the study of phenomenon of "relative" scarcity, which already presupposes that "scarce" goods can be substituted for other goods or that more of the scarce good can be produced by reallocating resources differently (Baumgärtner et al., 2006). However, while innovation response to scarcities has been studied extensively at a macro level (see e.g. Bretschger, 2005), our understanding of what drives technological substitution decisions made by those who actually decide to develop new technologies — the "technologists" — could still be improved (Bretschger, 2005). The open question motivating this study is the decision-making logic of the technologists: when and why do they choose to develop technological substitutes, and when do they adopt other courses of action?

The task of developing empirically grounded insights into the microlevel dynamics of induced innovation largely falls to the lap of innovation studies. Accordingly, an emergent "ingenuity" research stream within innovation and management studies has studied the concept of constraints and scarcities and their impacts for innovation (for overviews, see Lampel et al., 2014; Gibbert et al., 2014; Gibbert and Välikangas, 2004). This research has found, for example, that financial constraints may in some cases result to better performance from groups engaged in innovative work (e.g. Scopelliti et al., 2014; Hoegl et al., 2008; Keupp and Gassmann, 2013; Weiss et al., 2014; Katila and Shane, 2005), or that some scarcities have been solved through innovative solutions (Korhonen and Välikangas, 2014; Gibbert and Scranton, 2009; Gibbert et al., 2007). Other works note that "bottom of the pyramid" approaches to lean product development can produce superior products (e Cunha et al., 2014). Nevertheless, there is a gap between these positive microlevel studies and generally negative high-level econometric findings (Newell et al., 1999; Roediger-Schluga, 2004). Some scholars caution against drawing too firm conclusions from the research, as the overall outcomes of scarcities and constraints do not seem to accelerate technological change (Roediger-Schluga, 2004) or may only result to somewhat quicker adoption of technologies that would probably have been adopted anyway Korhonen and Välikangas (2014); Yarime (2007). If the latter case holds true more generally, the prospects of overcoming environmental and other scarcities through technology-

influenced discussions in e.g. policy sphere, or what Kwak (2017) calls "economism".

enabled substitution become significantly bleaker.

This paper seeks to answer the call put forward by Bretschger (2005) and build links between the scarcity and innovation literature through (mostly) theoretical but empirically informed discussion of the prospects of technology in overcoming scarcities. This study also expands upon prior case studies of scarcity-induced innovation or technological substitution (e.g. Hoogma, 2000; Gibbert and Scranton, 2009; Roediger-Schluga, 2004; Korhonen and Välikangas, 2014) and helps explain why some technologies may be easier to substitute than others.

My focus is on the fundamental choices made by those who develop technologies, rather than on the organizations where the technologies are developed. While the latter are undoubtedly of great importance for understanding how scarcities can induce innovation, the behavior of organizations facing scarcities has been studied in numerous fine studies already (e.g. Weiss et al., 2014; Hoegl et al., 2008; Katila and Shane, 2005; Galunic and Eisenhardt, 2001; Noci and Verganti, 1999). However, these studies are usually limited to financial constraints (i.e. the standard economic scarcity) and do not generally consider whether the technology used might have some influence in the outcome. Furthermore, prior studies have not explicitly addressed the decision-making by technologists (as individuals or as a group), even though it is individual people who actually make the decisions whether or not to attempt to develop substitutes. While the motivations behind important technological decisions are undoubtedly complex, I will attempt to outline some possibly rational reasons why technologists sometimes choose to develop substitutes, and sometimes resort to other means to secure access to required resources or simply cope with the scarcity. Even though this question could be sidestepped in a standard neoclassical analysis by arguing that technologists develop new technologies when the costs of inaction exceed the costs of action, I believe that a more detailed unpacking of the substitution decision would be valuable for advancing our thinking about resource scarcities and technological substitution.

Unfortunately, this focus on technological decisions will require me to abstract out the indubitably important role markets play in scarcity responses: for the purposes of this paper, the resource allocation role of markets is assumed to happen through cost/benefit calculations comparing various technological options. That said, I believe that the analysis can be readily extended to cover the role of markets, should a need arise.

The discussion here is necessarily interdisciplinary, requiring insights from several different research streams. From economics, I build upon recent thinking about the nature of scarcities, and particularly on Daoud's (2007; 2011) concept of "quasi-scarcities" as an additional type of scarcity besides absolute and relative scarcities (cf. e.g. Baumgärtner et al., 2006). From innovation studies, I draw upon increasingly influential theory of technologies as recombinations of existing mental and physical components (e.g. Savino et al., 2015; Fleming, 2001; Arthur, 2007, 2009). This "recombinatory innovation" theory provides a simple yet detailed enough view into inner workings of technological systems and how they can change as a response to scarcities. A particularly valuable lesson learned from recombinatory innovation theory is that the technologies are not alike. The interdependence of technology's components, for instance, can influence the difficulty of altering existing technological systems. As such, it should help us to understand better how, and when, scarcities can help promote innovation that effectively substitutes the scarce resource — and when we should be suspicious of techno-optimist claims.

The paper is structured as follows: first, a brief review of the concept of scarcity in economics, including Daoud's (2007; 2011) concept of quasi-scarcities; second, an introduction into recombinatory theory of innovation, followed by the main theoretical contribution — a model of recombinatory, scarcity-induced innovation. Next, this model is applied to two brief historical case studies to illustrate the mechanism in action. Finally, a discussion and conclusions are provided.

7.2 Scarcity economics: perhaps everything isn't relative?

A widely accepted definition of modern economics maintains that economics "studies human behavior as a relationship between ends and scarce means which have alternative uses" (Robbins, 1932, p. 15). As Baumgärtner et al. (2006) note, from this it is often concluded that economics is essentially about optimization under constraints, which are merely expressions of scarcities. However, Baumgärtner et al. (2006) and many others (for a review, see Daoud, 2011) have noted that modern, neoclassical economics defines scarcity only in a relative way. In this formulation, in order to obtain more of the scarce good A, one must give up something else, B. However, it is implicitly assumed that more of A will always be available, if only sufficient value of B is exchanged. In many cases, this is a reasonable simplification: as long as elementary resources are fairly abundant, giving up one consumption bundle ("A") allows the production of another bundle ("B"). Furthermore, people are often willing to accept such substitutions. Thus, goods are thought to be substitutable either on the production side or the preference side (Baumgärtner et al., 2006).

The extent to which this is the case in reality is, however, open to discussion. Many scholars argue that in practice, some resources may not be substitutable (e.g. Baumgärtner et al., 2006; Daoud, 2011, 2007; Tchipev, 2006; Raiklin and Uyar, 1996). Common examples include living species, which cannot be replaced if extinct; another example might be bread in a besieged, starving city (Baumgärtner et al., 2006). Although the distinction between essential and non-essential or "elementary" and "imaginary" needs may be fuzzy (Lähde, 2013), it seems obvious that at least in some extreme cases, some resources do not have viable substitutes. For example, humans need a certain amount of energy (food) to survive: for individual, arguably nothing can substitute for food if starvation is imminent.[3] In such settings, scarcity may occur due to human needs or wants exceeding the available resources. However, the problem can be examined even deeper. In a commendable effort in sorting out various types ofscarcities, Daoud (2011; 2007) synthetized the ideas of famous economists Amartya Sen and Carl Menger into a model of (quasi)scarcities and (quasi)abundances. For the purposes of this study, Daoud's important contribution is the (re)introduction of the concept of quasi-scarcity into scarcity discussion.

By quasi-scarcity, Daoud means a situation where goods are generally abundant, but (quasi-)scarcity still arises in respect of given individuals because of invalid or absent entitlement to said goods (Daoud, 2007). In Daoud's formulation, scarcity arises from a generative mechanism composed of needs R, entitlement E, and goods A. In cases where $R < A$, as is the case with world hunger and food supply (Daoud, 2007), a mediating mechanism E, access, is required for scarcity to occur.

As the purpose of this paper is to chart the decision-making process of individual technologists, the distinction between relative, absolute, and quasi-scarcities is important. While "outbreaks" of ab-

[3]Note though that an individual may choose to starve, for example to save resources for his/her children - or just to make a political point. Arguably, the benefit the individual receives from this decision is therefore a substitute for food. Similarly morbid arguments might be put forward to argue that oxygen in air or any other seemingly non-substitutable resource may also be "substituted." It is therefore a matter of definition and level of analysis whether substitution should be considered possible. For the purposes of this paper, I assume that some resources may be so difficult or ethically problematic to substitute as to be practically non-substitutable.

solute scarcities may occur at a system level, technologists generally operate on a lower level. At the firm or industry level, where most of the relevant technological change occurs, sudden onset of absolute scarcity is rare.

More common are quasi-scarcities, where — in principle — a good may be available, but access to the good is restricted. Examples abound in pollution control, where the "good" is the free use of natural "sinks," such as the atmosphere, for the purposes of waste disposal. In most countries, increasingly strict environmental legislation controls how much of this "good" individual firms may use. However, firms may attempt to influence their entitlement and lobby for less regulation. Examples of such efforts to alter firm entitlement are easy to find. For just three examples, one may look at the ignomious fate of the 1990s California Zero Emission Vehicle mandate (Kemp, 2005; Hoogma, 2000), the history of volatile organic compound (VOC) regulation in Austria (Roediger-Schluga, 2004), or the recent diesel car emission scandal, where several governments responded to news of automakers cheating in emission tests by proposing looser emission limits!

Why do technologists choose to lobby instead of developing new, profitable innovations? The short answer is because technologies are not developed from nowhere. No matter how attractive a solution would be, a technologist cannot even conceptualize a technological solution to a problem unless she has the mental building blocks required for the concept, and the concept cannot be realized until physical building blocks exist as well. If we want to understand better when we can rely on technology to deliver solutions to scarcities, we first need a working theory for how technologies are replaced with new ones. It is for this reason why we shall now introduce the recombinatory theory of innovation.

7.3 Recombinatory model of scarcity-induced technological response

Recent years have seen a resurgence of an idea dating back to Schumpeter and beyond (Schumpeter, 1934; Ogburn, 1922): that technologies can be fruitfully understood as systems composed of recombinations of existing "components" (Fleming and Sorenson, 2001; Arthur, 2007, 2009; Frenken, 2006; Fleming, 2001; Murmann and Frenken, 2006; Savino et al., 2015). These components include not just physical artifacts, but also practices and knowledge required to construct a particular technology (Arthur, 2009). Furthermore, technologies and technological systems themselves can become components for further technologies.[4] The recombination is usually performed in organizations such as firms, but it is ultimately the individuals — technologists — that make decisions whether to pursue some avenue of research or to recombine components in a specific manner. While the details of this recombination process are interesting and important (for a review, see Savino et al., 2015), for the purposes of this paper, the details are ignored and the catch-all term "technologist" is used to keep discussion manageable while referring to any decision-making body with power to make important decisions regarding the development of technological substitutes to scarcity.

By thinking about technological systems as combinations and decomposing technologies into their components (and, if necessary, further into sub- or even sub-sub-components) we can consider the interdependencies between the components (Fleming and Sorenson, 2001; Arthur, 2007, 2009; Frenken, 2006). Such interdependencies may in fact be important reasons why some scarcities may have significant impacts on technological systems, while others do not. As such, this theory answers the call put forward by Bretschger (2005, p. 161) for a "better understanding of the mechanisms driving [scarcity-induced] innovation". Finally, it should be noted that in this paper, the terms "technology" and "technological systems" are used rather loosely, following Arthur's (2009) definition of technology as some means for fulfilling a human purpose, whether that purpose is explicit or hazy.

Let us therefore consider an exemplary technological system T (Fig. 1). Let us assume that it consists of only two components X, and Y. These components are connected to each other to form the technological system T, i.e. $T = f(X, Y)$, for the purposes of producing a good A of some value, i.e. $A = f(T)$. The production of A requires two resources, I and O, from outside world. These may be understood as inputs or waste sinks, and may become scarce. Let us further assume that at least one of these resources is required to produce A.

For both of the resources, I or O, there may exist substitute resources $I_{1,\ldots n}, O_{1,\ldots n}$. However, using them may require changes in the technology T (to $T_{1,\ldots n}$). This change is effected by changing the technology's components X, Y to $X_{1,\ldots n}, Y_{1,\ldots n}$. It is worth

[4] Note that technological systems can be decomposed to different combinations of components depending on the level and purpose of analysis. For example, cars could be considered to be composed of only four main components (engine, drive train, steering and chassis) at one level of analysis (see Frenken, 2006), while at another level of analysis, cars are composed of thousands or hundreds of thousands of components. Similarly, the decomposition would change if we were to consider e.g. "mobility system" as a whole.

noting that the components are often composed of sub-components X', Y' of their own, and thus substitution may in fact change a sub-component (or sub-sub-component X'', etc...) of a component rather than the entire component; however, what exactly we consider a component and a sub-component depends on how we wish to divide a technology for analysis, and the division of technology into two components provides enough detail for the theoretical analysis now at hand.

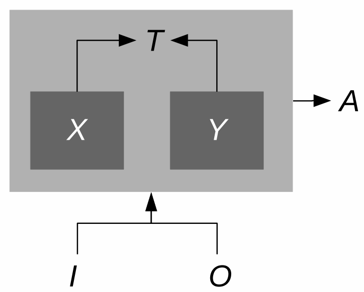

Figure 7.1: Exemplary technological system.

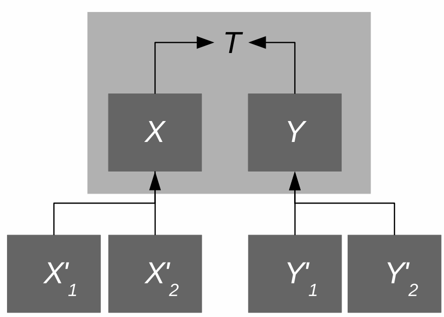

Figure 7.2: Technology and its sub-components.

Armed with this model of technological systems and Daoud's (2007) notion of relative, absolute and quasi-scarcities, we are now ready to examine how technologies might change as a response to scarcities, and consider the possibilities for substitution.

7.3.1 Availability of alternative technological components

In order to substitute component X with alternative component X_n, the sub-components X' required for X_n need to be available in the first place. (An important research finding is that particularly in breakthrough innovations, the needed components may come from an entirely unrelated field; see Schoenmakers and Duysters 2010 or for case studies, Korhonen and Välikangas 2014; Särkikoski 1999). Likewise, if the entire technological system T needs to be substituted with T_n, an alternative capable of producing the good A at some acceptable level needs to be available.

There are good reasons to believe that at least in the short term, scarcities (particularly quasi-scarcities and absolute scarcities) generally promote adoption of already existing, more resource efficient (and, therefore, often more complex) technological alternatives instead of research and development of completely novel solutions (for empirical evidence, see Mickwitz et al., 2008; Kemp and Pontoglio, 2011). Research and development tends to be slow and risky, whereas responses to scarcities are generally demanded relatively quickly. This view is supported by empirical research that suggests the most common response to tightening environmental regulation and other quasi-scarcities is the adoption of existing but more efficient technology (Christiansen, 2001; Mickwitz et al., 2008; Yarime, 2007; Kerr and Newell, 2003). In some cases, these technologies are already in use; in others, they are ready to be taken to use (Korhonen and Välikangas, 2014).

It may be theorized that in the short term, substituting technology T for alternative T_n requires that components X_n and Y_n required for T_n are perceived to be available without much development effort. In case of scarcity, the cost of scarcity needs to exceed the perceived cost of adopting T_n, including possible development costs. In the longer term, it is possible that the scarcity spurs development of the required components X_n and Y_n. However, from this it does not necessarily follow that such components will be found.

7.3.2 Simple case: no interdependencies between components

In the simplest case, the components X and Y are independent of each other and from each others' inputs and outputs ($X \perp Y$, $I \perp O$). In other words, changing the component X to alternative component X_n in order to utilize a substitute resource(s) I_n, O_n does not require changes in Y. In respect of good A produced at a "normal" equilibrium level A_{eq}, we can then detail the four possible outcomes of generalized scarcity impacting either I or O. For brevity, I shall focus on component X and resource I. Note also that throughout the following discussion, for the sake of the argument I shall assume that the demand for A is fixed. As plentiful literature on scarcity and voluntary simplicity stresses, scarcities can also be abolished if the need for a particular good can be reduced.

1. No alternative component X_n nor substitute resource I_n can be found that can be substituted for X or I so that Acan be produced above minimum viable threshold level $A_0 (A_0 \geq 0)$. This case might be considered as an example of absolute scarcity.

2. Either X_n and/or I_n can be found that allows production above A_0, but below "normal" level A_{eq}.

3. Either X_n and/or I_n can be found that allows production at A_{eq} (or close enough so it doesn't matter). In this case, substitution can be considered perfect.

4. Either X_n or I_n can be found that allows production at *above* A_{eq}. This case would correspond to scarcity-induced productivity improvement as theorized by e.g. Porter and van der Linde (1995c).

The *type of scarcity* has bearing on the possible response — or, more accurately, the type of possible response defines the type of scarcity. If we define absolute scarcities as those scarcities where substitution is impossible (outcome 1), we naturally assume that there is no response whatsoever that would correct the deficiency and allow business as usual to continue. At firm or even at industry level, such scarcities are most likely rare, but possible. Individual firms may become bankrupt because of environmental legislation, and some goods (for example, dodo fillets) are simply impossible to produce, even though they were possible to produce at some point in human history.

Similarly, outcome 4 is possible but unlikely in practice. While information asymmetries and organizational inertia may theoretically lead to situations where external pressure (scarcities, in this case) can force the companies to try harder and uncover productivity-enhancing improvements, these situations are likely to be rare (for one formulation of necessary conditions, see Ambec and Barla 2002; for a more thorough review, Roediger-Schluga 2004). Prevalence of such outcomes would beg the question, *why such improvements were not adopted earlier?*

Likewise, outcome 3 is unlikely. Strictly speaking, such an outcome would require that there are no costs associated with substitution. Another possibility could be that while substitution incurs some costs, it also produces some benefits, and the net effect is close enough to zero so as not to matter.

By far the most common case would seem to result to outcome 2 — a loss of production of A. Whereas in outcomes 3 and 4 the technologists would not have much of an incentive to try and improve the supply of the scarce resource and would be, by definition, incapable of doing so in outcome 1, such an incentive is clear in outcome 2. Furthermore, many if not most scarcities relevant to environmental economics today are not due to absolute lack of a resource, but result from regulatory constraints placed on the utilization of a resource. In Daoud's (2007) terms, these scarcities should be properly understood as quasi-scarcities: what the technologists lack is *entitlement* to a specific resource.[5] From this it follows that one expected response from technologists to threatening resource scarcities would be action to improve access to a resource.

Possible actions include, but are not limited to, obtaining more of the resource or increasing the entitlement via market or non-market means. An example of the latter is lobbying in the political sphere. Individual firms and industries can wield substantial political power, generally in proportion to their importance to national or regional economy. "Compliance costs" to regulatory constraints are a hotly debated issue whenever new constraints are proposed, and firms often expect politicians to provide generous support if costs are anything but modest (Roediger-Schluga, 2004). Particularly if such support is not forthcoming, firms are known to spend considerable effort in lobbying against legislation, and can manage to add and exploit loopholes to the extent that regulation becomes ineffective (Kemp, 2005).

It would therefore follow that technologists confronting scarcities have essentially three choices: Suffer the impacts of scarcity, substitute i.e. make improvements in their technology in order to cope with scarcity, or improve their entitlement to scarce resources through political action. It might be conjectured that the choice depends on the perceived pay-off, and is influenced by the perception of how difficult or expensive the substitution would be. This brings us to the more complex question: Why some technologies are

[5] In Daoud's formulation, "regular" scarcity due to opportunity costs would tend to amount to "relative" scarcity.

inherently more difficult to substitute than others?

7.3.3 Substitution and the interdependency between components or resources

No discussion about the possibilities of technological substitution is complete without a reference to whale oil being substituted by kerosene as lamp fuel, and I do not intend to make an exception. Although the story is not quite as convincing example of technological substitution as it is sometimes claimed to be (see Kovarik, 1998), it serves to illustrate why some substitutions will be inherently easier than others. A major reason why alternatives to whale oil were rapidly adopted was because the fuel was not *interdependent* with oil lamp technology at the time. Users did not have to buy new lamps: they only had to purchase different fuel. In contrast, the replacement of gas lighting by electricity required not only new lamps, but an entirely new delivery infrastructure as well.

The theory of technology as recombinations of components presented earlier helps us to make sense of the importance of interdependencies. Typically, components comprising a technological system are to some extent interdependent from each other. Thus, an alteration of one component or its replacement necessitates alterations in other components. The more alterations are required, the more difficult replacing a particular component will be. Furthermore, required resources may also be interdependent with other components, or required resources may themselves be complementary to each other. In the model technological system described above (Fig. 1), if the good A can be produced with either resource I or O, the inputs are independent ($I \perp O$); if the production (above threshold A_0) requires both, then the resources are interdependent, or complementary. Interdependency of resources increases the difficulty of substitution in the same way as the interdependence of other components of the system.

These interdependencies can be formalized and modeled in various ways. One popular formulation that has been repeatedly used in studying dynamics of innovation and new product development (Frenken, 2006; Silverberg and Verspagen, 2005; Almirall and Casadesus-Masanell, 2010) is the so-called *NK*-based simulation model of complex systems(Kauffman, 1993). Without going deeper into details of this model (the reader is directed to Frenken 2006, for excellent discussion of the model and its application to innovation research, or to Savino et al. 2015 for empirical evidence concerning search and recombination processes), it can be used to conceptualize the design of technological artifacts as a search problem over “design landscapes” (Kauffman et al., 2000; Katila and Ahuja, 2002; Frenken, 2006; Maggitti et al., 2013; Savino et al., 2015). The topology of these landscapes depends on the interlinkedness of technology’s components, with one dimension representing “fitness” — in technology studies, usually interpreted as efficiency or quality (Frenken, 2006). As interdependencies increase, the number of trade-offs required also increases: improving one part of the system degrades the performance of another part. Topologically speaking, the number of “local optima” of high fitness regions increases from one optimum (achievable if there are no interdependencies, as then every component can be independently optimized) to many. This is an intuitively appealing formalization of the typical design problem faced by technologists: everything has a trade-off, and the more complex the product, the more complex the trade-offs. Even more importantly, the model shows that moving from one local optimum to another requires alterations in several of the technology’s components at the same time.

Therefore, the search for alternative solutions becomes more and more difficult as the degree of interdependency grows. Systems whose components are independent of each other can be relatively easy to adapt to scarcity of some particular component or input: The search for new solutions can be confined to searching alternatives for that particular component or input. But if interdependencies are present, several components or even the entire system may need to be revamped at once. Aside from vastly increasing the theoretical difficulty of the search problem (see Simon, 1969), in the practical realm this may very well mean a requirement to build or to prototype and test a replacement for the entire system instead of its component only. Obviously, this may be an expensive proposition.

7.3.4 Complexity growth as a scarcity response: is efficient = good?

In this light, technological systems with fewer interdependencies could be considered more resilient and likely to adapt to scarcities through technological substitution. Unfortunately, evidence in form of simulation studies (Altenberg 1997; Kauffman 1993; note that *NK* models are generally not amenable to analytical solutions and require simulation studies), empirical investigations (e.g. Fleming and Sorenson, 2001) and plentiful anecdotes strongly suggests that such “functionally independent” systems[6] would generally be

[6] Strictly speaking, no actual “system” can consist of totally independent components. The term “functionally independent” is therefore used.

less efficient in their primary purpose than moderately interdependent systems. (Heavily interdependent systems, on the other hand, suffer from "complexity catastrophe" and would be difficult to design in the first place; see Frenken 2006 or Simon 1969 for thorough discussion.) In real-life terms, a system whose components were functionally independent would suffer from significant design penalties: for example, if the skin and chassis subsystems of a car were to be functionally independent, the chassis as a whole would be significantly heavier, as the skin could not be counted to double as a load-bearing component. Thus, in reality, moderately interdependent systems are far more common than systems whose components are functionally independent. This is a powerful theoretical explanation for the generally accepted wisdom: efficiency and resiliency are usually mutually exclusive goals.

Ironically, the very pursuit for increased "efficiency" that is often touted as the key technological response to environmental problems, e.g. for climate mitigation, may well make the system as a whole less able to cope with other scarcities. What's more, the drive for improved efficiency usually results to what Arthur (2009, p. 134) calls "structural deepening," where the deficiencies of originally simple technologies are amended by adding more and more complex components. This in turn provides many more opportunities for webs of interdependency to build up and clog the system as a whole. As an example, the early (and by current standards extremely inefficient) jet turbine prototype of 1936 had one moving part and at most some hundreds of parts in total: current jet engines have more than 20 000 parts. Efficiency improvements, a typical scarcity response, usually involve structural deepening and an increase in complexity. This may have repercussions later, if increased complexity makes total system change more difficult.

7.3.5 The types of scarcity and technological substitution

Assuming a profit-maximizing firm using technological system T (Fig. 1) and a scarcity of resource I, the following lists the five different types of scarcities and technological response, i.e. potential outcomes depending on whether demand for good A is elastic or inelastic. In the former case, there are effectively ample substitutes for A, whereas in the latter case, the scarcity of A itself may be a serious problem.

I. I scarce in the sense of it having an opportunity cost; demand for A elastic: *Relative scarcity.* Standard economic optimization problem. The possibility for substituting technology T or component X by technology T_n or component X_n in order to utilize more abundant resource I_n depends on the availability and cost of T_n or X_n and/or availability and cost of I_n. The substitution cost depends also on the degree of interdependency between technological components: high degree of interdependency suggests (but does not necessitate) that technological substitution is less likely. Can induce development of T_n or X_n over longer term, but is unlikely to significantly accelerate the pace of technological change.

II. I scarce because of insufficient entitlement; demand for A elastic: *Quasi-scarcity of I, relative scarcity of A.* If technological solution is perceived to be within reach, tends to result to technological response depending on cost and availability of T_n, X_n and I_n, as in case 1. However, insufficient entitlement can also be amended through political action, or through a combination of technological substitution (to reduce the impact of scarcity) and political action. Can also induce development, and if alternative T_n exists and will involve only modest loss from A_{eq}, is likely to accelerate adoption of T_n.

III. I scarce because of insufficient entitlement; demand for A inelastic: *Quasi-scarcity of I and of A.* Most likely response is political: inelasticity of demand for A gives the technologist considerable political clout. However, if alternative T_n exists or is perceived to be close to practical feasibility, it is very likely to be adopted as one part of the solution, even if it involves significant loss of value from A_{eq}.

IV. I absolutely scarce; no quick technological or political fixes perceived; demand for A elastic: *Absolute scarcity for I, relative scarcity for A.* Leads necessarily to reduced production from A_{eq}. Tends to spur research and development for alternatives and is likely to promote adoption of alternative T_n if such technologies exist, despite potential loss from A_{eq}.

V. I absolutely scarce; no quick technological or political fixes perceived; demand for A inelastic: *Absolute scarcity of I and A.* If I used to be abundant, this situation is likely to lead to problems in broader techno-social system, unless research or political action produces alternatives relatively quickly.

In other words, the existence of absolute scarcity depends on the perceived possibility for substitution. We can talk meaningfully about absolute scarcities only if there are no substitutes for either the scarce resource *or* for the good produced from the resource. Since this is not a common occurrence, it follows that cases of absolute scarcity are rare, and lack of availability of cases to study may alone explain why research so far has largely ignored the possibility of absolute scarcities. (Note that cases where I is scarce but technological or political solutions are readily available are not discussed above; it is assumed that in such a case the substitution decision will be simple.)

It is important to note that since research and development decisions involve essentially predictions about the future, the decisions tend to be based on *perceptions* of what is feasible and what is not. Technologists are unlikely to be able to assess the costs and risks of a development effort reliably enough for truly calculated choices about which course of action to pursue. For this reason, mental models, perceptions and social constructions of the technologists (see Kaplan and Tripsas, 2008) are likely to be of considerable importance for any attempts to assess the likely response to scarcities.

In the following section, I use the model above to illustrate two previously published cases of scarcity-induced innovation.

Scarcity of I			
	Absolute	IV. Absolute scarcity for *I*, relative scarcity for *A*. Decrease in production of *A*. May promote R&D.	V. Absolute scarcity for *I* and *A*. Can cause societal problems if situation persists.
	Entitlement (quasi-scarcity)	II.Quasi-scarcity for *I*, relative scarcity for *A*. Likely responses technological and/or political.	III. Quasi-scarcity for *I* and *A*. Likely response political, unless alternative technology ready.
	Opportunity cost (relative)	I. Standard economic optimization problem: production of *A* depends on costs of *I* and demand for *A*.	
		Elastic	*Inelastic*
		Demand for A	

Figure 7.3: Responses as a function of scarcity type and elasticity of demand.

7.4 Example cases: scarcity in jet engine development and copper manufacturing

Technological response to resource scarcities has been studied in two relatively recent case studies, one focusing on the development of jet engines in Second World War Germany (Gibbert et al., 2007; Schubert, 2004; Gibbert and Scranton, 2009) and the other on the development of radically novel "flash smelting" technology in copper smelting as a response to post-Second World War energy scarcity (Korhonen and Välikangas, 2014; Habashi, 1993; Särkikoski, 1999; Habashi, 1998). Drawing on historical approach, these studies illustrate how a perceived scarcity caused technologists to develop novel innovations in response, effectively substituting technology for scarce resources. Both cases have been hailed as exemplaries of potential benefits of scarcity for innovation (Gibbert et al., 2007; Schubert, 2004; Gibbert and Scranton, 2009; Korhonen and Välikangas, 2014; Habashi, 1993; Särkikoski, 1999; Habashi, 1998), and as such, they serve as good examples to demonstrate the framework outlined above. The history serves to tell three stories: two of success, and one of failure, demonstrating how radical changes that cause a cascade of changes throughout the technological system can be too much of an obstacle, as noted in the Section 3.3.

7.4.1 The substitution of nickel in early German jet engines

The efficiency of a jet engine is heavily dependent on the maximum temperature the engine parts can withstand. The higher the operating temperature, the more efficient the engine can be. In particular, early jet engines were limited by the temperature their turbine parts tolerated. In a jet engine, turbine at the rear end of the engine is powered by hot, expanding gases from the combustion chamber, and convert some of the energy in gas to rotary motion. This motion drives the compressor at the engine's front, pushing more air into combustion chamber between the compressor and the turbine and thus enabling the engine to operate (Fig. 3).

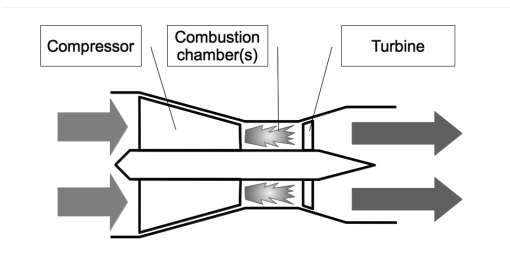

Figure 7.4: A schematic of a jet engine.

A major problem for turbine design is that turbine blades in particular have to withstand very high temperatures while being stressed by turbine spinning extremely rapidly. Materials suitable for practical jet engines only appeared in the 1930s, in form of nickel-based "superalloys" (Sims, 1984). However, at the time nickel was a scarce strategic resource, essential for a variety of military equipment from tough armor plate to armor-piercing projectiles and machine tools required for manufacturing armaments. In particular, nickel posed a problem for Germany: most of the world's nickel supply was in the hands of the Allies (Perkins, 1992).

The "success:" hollow turbine blades

According to some researchers, the nickel scarcity faced by German jet engine designers spurred them to come up with a novel, radical innovation: a turbine whose blades were cooled by air via a system of internal air ducts (Gibbert et al., 2007; Schubert, 2004; Gibbert and Scranton, 2009). Hence, the nickel shortage is argued to have resulted to a remarkable innovation that managed to substitute for scarce nickel.

However, another interpretation of the same set of facts is that the perceived availability of a technological solution may have *exacerbated* the scarcity. The air-cooling concept adopted by the Germans, called the "hollow blade" (that is, a hollow turbine blade made from thin sheet metal) to distinguish it from modern "cooling channel" concept (Gunston, 2006; Kay, 2002, see Fig. 4) had its roots in the pre-war designs for piston engine superchargers (Lorenzen, 1930; Reinburg, 1930; Smith and Pearson, 1950). Turbochargers contain a small turbine, powered by hot engine exhaust, that turns a compressor that forces more air into the piston engine. Thus, they are in effect small jet engines with an external combustion chamber. They share many similarities with actual jet engines (which are powered directly by hot gas generated in the internal combustion chamber) and the early jet engine designers almost invariably had experience with or were inspired by existing turbocharger designs. From the 1920s, German turbocharger designers had experimented with hollow blades to design turbochargers that would both require less nickel (which was known to become scarce if a war were to break out), and be easier to manufacture, as stamped and welded sheet metal blades could be much cheaper to make compared to laborious milling of solid blades (Giffard, 2016). Coming from this background, the German jet engine designers continued to develop hollow blade concepts for both of these reasons, with ease of manufacturing actually being the dominating rationale according to immediate post-war interviews (Sproule, 1946).

Some later recollections indicate that the designers did perceive

Figure 7.5: Original and modern air-cooled turbine blade cross sections. The original German hollow blade design (left) was made from thin sheet metal; modern turbine air cooling (right) uses very different turbine blades with cast and machined cooling channels.

the nickel scarcity as a pressing one (e.g. von Ohain, 2006). However, as shown by the data collated in Norcross et al. (1947), the scarcity was more a question of insufficient entitlement rather than absolute lack of resource: Germany ended the war with more nickel reserves than it had at the beginning. Even the most ambitious jet engine program envisioned by the Germans would have consumed only a minuscule portion of the reserve stocks, and would actually have *conserved* nickel resources, even without the hollow blade design: jet engines of greater power could be manufactured with less nickel and other scarce materials than state of the art piston aeroengines (based on figures in Kay, 2002; see also Giffard, 2016). As such, the evidence suggests that the development and promise of hollow blade designs caused the German air ministry to see no reason to increase the nickel allocation to the jet engine program; as a consequence, the designers continued to operate under the perception of nickel scarcity.

While advantageous from the manufacturing point of view, the hollow blade design imposed definitive performance penalties and design complications (Wilkinson, 1946; Kay, 2002, see Fig. 5.). These complications, which included the need to route cooling air inside the engine, illustrate the typical tendency of technological solutions to scarcity to have interdependencies to other components of the system, and how technologies tend to grow more complex in in response to scarcities (see Sections 3.3 and 3.4). These and the performance trade-offs were the key reasons why the British — the other leaders in jet engine development — did not adopt air cooling in their early designs despite testing it (Eyre, 2005; Gunston, 2006). In contrast, the Germans accepted decreased performance, forgoing the slight but very real advantage afforded by more powerful engines in World War II aerial combat. As such, the jet engine case could be seen as an example of Type II scarcity discussed earlier: the demand for good A, in this case performance, was at least somewhat elastic, while the nickel shortage was a quasi-scarcity arising from insufficient entitlement rather than absolute shortage of nickel. Furthermore, as discussed above, the perception of a technological

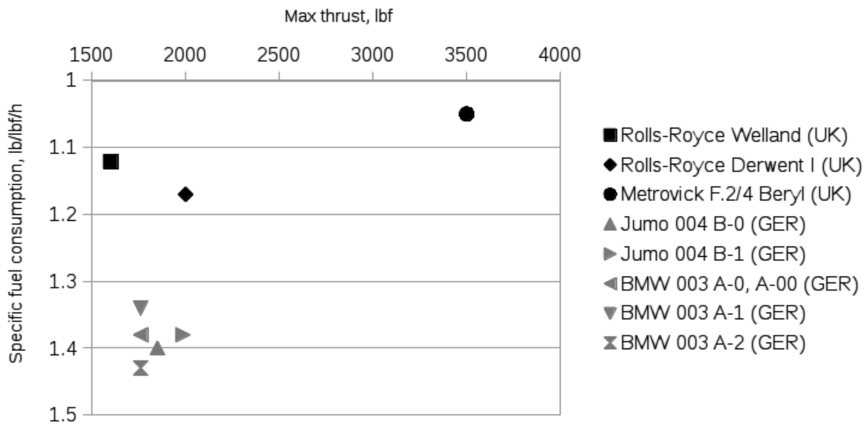

Figure 7.6: Performance and fuel efficiency of Second World War-era jet engines. Performance (maximum static thrust) increases towards top right. Data from Wilkinson (1946) and Kay (2002).

solution being available may have been a factor in preventing the political solution of the scarcity.

In this case, the technologists may not have made a conscious decision to develop a technological substitute for scarce nickel, although the desire to save nickel was clearly a part of the appeal of the hollow blade turbine and contributed to the support the design enjoyed despite protracted development (Kay, 2002). However, by continuing to develop a technology that was likely perceived at least as a partial substitute by their superiors, the *in*decision of German jet engine designers contributed to the perception of scarcity, and to continued lack of entitlement to scarce nickel resources. The demand for performance A was sufficiently elastic to permit some performance penalties, and as a whole, the problem did not become sufficiently acute for a political response (increased entitlement) that is more likely in Type III scarcities, where the demand for A is inelastic.

The failure: ceramic turbine blades

It should also be noted that the nickel scarcity did not cause the German designers to succeed in developing a truly revolutionary design: a ceramic gas turbine. Ceramics, naturally resilient against high temperatures, would in theory have been excellent answers to nickel shortages, as they could have been made from abundant alternative resources. The Germans tried to develop ceramic components such as turbine blades and nozzles for jet engines as well, but they lacked the technological sub-components required to make them work (Kay, 2002). This illustrates nicely the idea put forward in Section 3.1: the required technological components, which may come from an entirely unrelated field, need to be available for scarcity to bring about novel innovations. Even today, practical ceramic jet engines remain in the drawing boards, and it is not clear which technological developments are required to realize them — if that even happens (Gunston, 2006).

While test rigs and some prototype engines were nevertheless built and run with ceramic turbine blades, the use of ceramics necessitated major changes in the overall engine design and eventually rendered the resulting engines impractical from either operational or, more commonly, manufacturing point of view (Kay, 2002). This serves as an example how the inherent interconnections between the components of the technological system may make substitution difficult if not impossible, because changes in one subsystem can cause a cascade of changes throughout the system as a whole.

7.4.2 Substituting electricity in copper smelting

Another relatively well-documented case where technological development has been claimed to have benefited from scarcity concerns the invention of so-called "flash smelting" technology for copper smelting. When developed in the late 1940s, this technology made possible to eliminate or at least greatly reduce the need for extraneous fuels in smelting copper ore to raw copper, and potentially halved the cost of smelting (Korhonen and Välikangas, 2014; Habashi, 1993; Särkikoski, 1999; Habashi, 1998). As its effluent gases were also easier to clean compared to many previous furnace types, it is no wonder that flash smelters accounted at one point for nearly 70 percent of world's primary copper production (Korhonen and Välikangas, 2014; Särkikoski, 1999).

The roots of this remarkable energy-efficient innovation are often traced to the post-war energy crisis that faced Outokumpu Ltd., a small state-owned copper manufacturer in Finland. As a result of defeat in the Second World War, Finland lost a significant chunk of its electric generation capacity. Just prior to the war, Outokumpu had invested heavily in a large electric smelter, and now had to quickly develop an alternative. The situation was critical: Outokumpu's copper products featured prominently in the war reparations deliveries the victorious Soviet Union demanded from Finland, and a failure to comply might have even been used as a pretext for military occupation (Kuisma, 1985; Rautkallio, 2014). The invention of the flash furnace was later seen as almost an miraculous solution to this pressing problem.

However, while the electricity shortage was the proximate cause for Outokumpu to begin work on flash furnace, the furnace type itself was a result of decades of well-published experiments and practice, and was simultaneously and independently taken into use in Canada (see again Section 3.1). In fact, the alternative design was technologically superior (Korhonen and Välikangas, 2014). Furthermore, Korhonen and Välikangas (2014) argue that Outokumpu had other options at its disposal, and that its politically well-connected managing director Eero Mäkinen could very well have pressured the government, which in any case owned the firm, to divert more electricity or coal (an alternative fuel) to its use. Both resources were scarce, but arguably not absolutely so. Using data on Finnish energy usage and archival records attesting of Outokumpu's importance to the Finnish goverment, Korhonen and Välikangas demonstrate that either of these options could have been feasible when the decision to develop the flash furnace was taken in late 1944, and that they might have been even more prudent choices than embarking on a quest for untested technology. However, the confidence Outokumpu's engineers had on the flash smelting furnace meant that the company's chief decision-maker Mäkinen did not perceive a real need for alternatives, and hence had no pressure to lobby the government for these resources for Outokumpu's use — in stark contrast to the lobbying the same managing director embarked upon when certain other resources, arguably much less critical for Outokumpu, were scarce (Korhonen and Välikangas, 2014).

The pressure from war reparations deliveries suggests that this case could serve as an example of Type III scarcity response: the resource I, energy, was available but not allocated in sufficient quantities, while the demand for A, copper products, was more or less inelastic. While the most likely response might have been political (that is, Outokumpu's managing director lobbying for higher entitlement), the perception that an alternative technology was readily available, combined with the managing director Mäkinen's demonstrated patriotism (Särkikoski, 1999), caused Outokumpu to refrain from squeezing more resources from the hard-pressed government. In this case, the decision-making culminated in a single person: Mäkinen. He had been directing the company since 1918, and was a forceful personality (Särkikoski, 1999; Korhonen and Välikangas, 2014) who by 1944 ran the notionally state-owned company pretty much as his own fiefdom. Research has shown that he perceived flash smelting to be a feasible if not 100 percent certain solution to Outokumpu's problems (Särkikoski, 1999; Korhonen and Välikangas, 2014), and directed the company's engineers accordingly.

The simultaneous "discovery" (more properly, development) of flash smelting in Canada and the long "pre-history" of the innovation (documented by Korhonen and Välikangas, 2014) show that Mäkinen's perception was based on evidence, and that the development of flash smelting was not just a serendipitous discovery. The time was ripe for flash smelting, and the electricity scarcity just provided the impetus for *Outokumpu* to be among the first companies to actually build furnaces implementing the technology. An additional insight worth noting is that several components required (understanding of fluid bed reactions and oxygen generators) came from fields totally unrelated to copper metallurgy, just as discussed in Section 3.1, and that the flash furnace was very much more complicated than the earlier coal-fired and electric furnaces it eventually replaced, demonstrating the structural deepening of a technological system when its efficiency is increased (Section 3.4).

7.5 Conclusions and discussion

In this paper, I've attempted to shed some light into a question of great practical and theoretical importance: why and when do technologists choose to develop technological substitutes for scarce resources, and when do they act to increase their resource entitlements? The answer that emerges is complex, as is to be expected from such a broad question. There are different types of scarcities, and depending on the maturity of relevant technologies, the possibilities for technological substitution may differ. Building on previous work on the nature of scarcities (Bretschger, 2005; Baumgärtner et al., 2006; Daoud, 2011, 2007; Raiklin and Uyar, 1996; Roediger-Schluga, 2004), one key contribution of this study is to underscore that while the type of scarcity matters, it is actually the perceived possibilities for *mitigating* scarcity that determine how the scarcity is perceived. If the scarce resource can be substituted easily, is it meaningful to speak of scarcities? The answer to this question seems to depend largely on the timescale and scope of the case in question. For individual firms for example, it may not matter if a technological substitute exists, if they lack rights or know-how to use it. On the other hand, such cases may not even register as scarcities on economy-wide level — although Roediger-Schluga (2004) and others warn that industries have political power and are often willing to use it to increase their entitlement to scarce resources, even to the detriment of the society as a whole.

In turn, the ease of which a technological substitute may be found may depend heavily on the particular technology in question. Technologies are not alike, and recent research (Arthur, 2007, 2009; Frenken, 2006) has given us many tools for peeking into their interior, what was once called the "black box." By considering technologies as recombinations of existing components with some interdependencies among each other, and considering the impact of a scarcity as a situation requiring change in one or more components, we can better understand why some scarcities seem to be amenable to technological substitution, while others stubbornly resist the best efforts of Earth's scientists and engineers.

Consider, for example, the "scarcity" of low-carbon energy that is currently imperiling our efforts at preventing dangerous climate change: the reality is that "dirty" energy derived from fossil fuels has become highly interdependent component in the world's economic system. As a result, attempts to replace fossil fuels with cleaner energy are threatened not only by technical difficulties, but by the political power resulting from the numerous interdependencies and the technical and economic difficulty of substitution: it is often easier, cheaper and more reliable to lobby for keeping the entitlement of fossil fuels (or pollution permits) than to completely overhaul the energy system. In contrast, the phaseout of ozone-destroying CFC gases was relatively simple problem, as almost "drop-in" substitutes for most of their important applications were available and phasing out the production of these gases had, at most, a limited impact on the bottom lines of few chemical manufacturers.

Furthermore, given that innovations have to be combinations of available components, it follows that expecting major acceleration of technological change as a result of scarcity is probably going to end in disappointment. If the necessary components are not available, to what extent a scarcity can spur their development? In cases where the necessary components are identified and the innovation is only waiting for further refinements in these components, this is probably possible, although far from certain. The flash smelting case referenced to in this paper provides a good example: According to Korhonen and Välikangas (2014), the technology was "in the air" at the time, generally anticipated by experts and waiting for some firm to adopt it and work out the remaining kinks. But many innovations result from unexpected and unanticipated bricolage of previously unconnected components. If such components are available, scarcity may provide the final impetus required. If they are not, directing research and development efforts to precisely the right components (or sub-components) is going to be difficult, as exhibited by the German failure to develop a viable ceramic turbine. As another example, cheap, large-scale battery storage of electricity has been a goal that has eluded inventors since Edison, even though economic and social benefits would be immense. Maybe technological change marches to a beat of its own, influenced by but not really controlled even by the best efforts of technologists, policy makers and regulators?

Finally, the theory and cases discussed in this paper suggest that while the ability to distinguish between "relative" and "absolute" scarcities may be of utmost importance and the current mainstream economic thought may be lacking in this regard, the cases of technological substitution that have been studied so far seem to be mostly concerned with either relative or quasi-scarcities and insufficient entitlement. The theory presented here provides one explanation why: technological substitution of absolute scarcities may simply not produce cases worth studying, because technologists have little interest in attempting what they expect to be impossible.

These biases may present a dangerous logical trap. As noted above, we generally define the type of scarcity by the ease with which we can mitigate its impacts: those scarcities that are easy to circumvent become, in retrospect, known as relative scarcities, while scarcity of something we can't substitute will be understood as absolute scarcity. However, since almost by definition there are few examples where absolute scarcities have been mitigated through substitution, the studies of substitution are mostly concerned with relative (or quasi-) scarcities. This in itself is not a problem: the problem lies in the way mainstream economic thought tends to assume *based on these studies* that every scarcity will be, in principle, substitutable. In one sense, this is true: every scarcity mainstream economics has so far studied has been solved through substitution of some sort. But what of those cases that leave no story of substitution behind? Is research on economics and technological change really representative in this regard, or dangerously biased? On the other hand, one could probably argue that "absolute" scarcities as such do not exist: even a person dying of hunger may very well choose to die so that someone else has more to eat. Presumably, the dying person will gain some mental reward for such an action that suffices to substitute for dying of hunger. It seems that advancing our understanding of what scarcities actually are and how we should think about them would present a fruitful arena for further empirical and theoretical study.

In conclusion, despite the potential importance of the questions of scarcity and their mitigation through technological substitution, research to the subject is still only beginning. This paper has promoted the use of more nuanced concepts of scarcities and technologies in order to advance the discussion, and found that by some reason or other, much of the existing research may not provide much basis for discussing the potential impacts of absolute scarcities. It remains an open question whether the concept of absolute scarcity has much actual meaning in this sense.

Research-wise, this study should provide some grounds for further studies in the area of technological substitution and technological change as a response to changing resource endowments. If possible, research should try to find examples of absolute scarcities being overcome by technological change or other means. Studies in this topic would help greatly in avoiding the bias described above. Another promising research direction might be the study of the mechanisms of how resource *abundance* (or quasi-abundance) might influence technological change. Finally, since this paper seeks to provide an overview of technological responses to various types of scarcities, focusing in more detail on technological responses to relative-, quasi-, and absolute scarcities might be a fruitful direction for future research. One possibly important link between scarcity and innovation literatures might be forged by examining what organization theory, for example institution theory, might have to say about how quasi-scarcities are formed and perpetuated.[7]

Policy-wise, I hope this study helps to demonstrate that the assumption of technology marching over scarcities through simple mechanisms of supply and demand should at last be laid to the grave where it belongs. The main policy implication of this paper is simple: politics matters a great deal, but while politically enacted quasi-scarcities can sometimes steer innovation to a desired direction, policy-makers should not rely on that happening. Technologists and technological developments can often influence the policy, and if advances to some direction are perceived as impossible, then no amount of political prodding is likely to produce meaningful results, while attempts to do the impossible are all too likely to squander political capital and opportunities. On the other hand, these perceptions can be misleading: whether to trust technologists or not remains a matter of fine judgment. In any case, this study should serve as another justification (if any more are needed) for the

[7]I thank the anonymous reviewers for pointing out these possibilities.

importance of broad-spectrum long-term, patiently funded research and development that (sometimes accidentally) produces technologies and components needed for technological substitution. Because components for a breakthrough may come from a surprising source, short-term, narrowly focused research efforts are unlikely promote the development of breakthrough innovations.

Policy-makers should also remember that efficiency and resiliency can be mutually exclusive goals. Striving for maximum efficiency in resource use can result to a system that is, as a whole, less resilient against unexpected challenges. Structural deepening and increasing complexity of more efficient systems therefore present a challenge to politicians and other decision-makers: Is resource efficiency always a good thing? Answering this question in more detail is another promising and valuable avenue for future research.

7.6 Acknowledgements

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Chapter 8

Learning from scarcities

What we can — or should — learn about scarcities and technology?

8.1 Introduction

The previous four chapters have looked at the interplay between scarcities, constraints and technological change from a variety of angles. However, the essays themselves offer little opportunity for drawing together the lessons learned during this project. This chapter, therefore, attempts such a conclusion. The final chapter will then provide some directions for future research.

In the following sections, I will first discuss the biggest question motivating my thesis — whether or not we ought to worry about scarcities. I present a brief critique of the two most common thought patterns in public discourse, the business-as-usualism and resource pessimism, and point for a way forward through resilience literature. Next, I try to answer the secondary question: do scarcities promote novelty? This brief section is followed by a discussion about how scarcities are often socially constructed rather than being "real" in the strictest sense, and a slight expansion of Daoud's (2007; 2011) concept of quasi-scarcities. This concept is of some importance as it permits a discussion of power relationships as a factor in resource scarcities and coping mechanisms to scarcities, a topic I would wish to see more research attention in the future. I also note that if the scarcity is caused by a power imbalance, technological development may in fact *perpetuate* rather than mitigate the scarcity through a mechanism I call "mental rebound effect". Finally, I outline some of the ways in which scarcities and constraints of material or energy resources could be distinguished, if the goal is to have a more informed discussion.

8.2 Should we worry about scarcities?

Perhaps the most pressing issue motivating my original research was the big question: should we be concerned that scarcities of key resources will have deleterious effects upon our lives, jobs, or society? Even though two brief case studies presented in this thesis cannot possibly answer a question of such magnitude, I nevertheless feel qualified to share my thoughts about the subject.

Warnings of an impeding societal disaster due to a lack of some specific resource have been a perennial thread in Western thought. Particularly after the publication of the influential *Limits to Growth* (Meadows et al., 1972), there have been periodical if inconclusive skirmishes between those who argue that resource constraints of various sorts will cause major upheavals and perhaps, ultimately, doom the modern civilization — at least, unless some drastic actions are undertaken (e.g. Heinberg 2003; Greer 2008; Heinberg 2004; Kunstler 2006; Sorman and Giampietro 2013) — and those who believe such fears overstated (e.g. Bruckner 2013; Simon 1998. For two overviews of the debate, see Homer-Dixon 1995; Sabin 2013.)

Despite the fundamental importance of this question, it seems unlikely that definitive, universally acceptable answers will ever be found. At its core, the resource constraints and societal collapse debate have not been, nor they are ever likely to be, about questions that are amenable to objective answers. Instead, the debate about resource scarcities and potential societal collapses has for a long time been a proxy battle between differing conceptions of humanity and our relationships with nature and each other (e.g. Sabin, 2013; Bruckner, 2013; Phillips, 2015). In general, those who see that tragedy is the essential human condition tend to believe we're heading for more or less inevitable collapse, whereas those who see the story of humanity as a triumph or believe in loosely defined "progress" (or its modern implementation, "innovation") also tend to believe that we can surmount whatever obstacles we may encounter. The central question of this debate (see e.g. Sabin, 2013; Phillips, 2015; Simon, 1998; Greer, 2008) can perhaps be phrased as thus: does our capability to invent new and useful things free us from the Malthusian trap of consumption rising beyond what our resource endowment can provide?

In other words, this important question can be largely rephrased as a question about the possibilities and feasibility of *technological substitution* of scarce resources, that is, natural capital. The scientific literature on the question is predictably divided. On one hand, those who hold what is sometimes known as "weak sustainability" position (Ayres, 2007) argue that practically all kinds of natural capital can be substituted by technological capital. On the other hand, those holding a "strong sustainability" position (Ayres, 2007) reject this assumption and argue that many if not most fundamental services the nature provides cannot ever be substituted by humans.

Because this question is so much a question of competing identities, attempts to "solve" it in any meaningful manner seem doomed to fail. However, what we may instead hope to achieve is to sharpen the debate and provide new ways of thinking about whether our society is at risk of collapse because of resource scarcities. After all, our attitudes and beliefs towards resource scarcities play a central role in the field of environmental governance, or interventions, decision making and behaviors, including regulation and other mechanisms, through which political actors influence environmental actions and outcomes (Lemos and Agrawal, 2006, p. 298). Currently, many plans and policies of scarcity (cf. Lähde, 2013) are painted with the broad brush of mainstream economic thought (see e.g. Homer-Dixon, 1995; Duffy, 2005).[1] However, even if the brush used were to be its equally broad neo-Malthusian antithesis, successful outcomes would seem unlikely.

8.2.1 The problem with business-as-usualism

A standard refrain from those influenced by mainstream economic thought is, in effect, to state that if substitutions haven't happened, then the reason must simply be that the resource constraint hasn't been pressing enough. After all, in theory substitution should occur once price of scarce resource rises so high that alternative spending bundles are more attractive. While theoretically sound, this statement is empirically problematic, being an example of circular reasoning: all too often, those arguing this position conclude from the observation that some resource hasn't been substituted that the reason for this non-event must be that the resource is not scarce enough for substitution to kick in. However, there are no laws of

[1] The critique of economic thought presented here is *not* directed at economic theory itself or against practicing economists, who in general are all too well aware of the limitations of their theoretical models. Rather, the criticism concerns the economics-influenced thought models prevalent in public discourse (see e.g. O'Connor, 2010). In much of current discussion, politics included, the "bastardised" theory of scarce resources being automatically substituted once price signals are sufficiently urgent still holds sway.

nature that state this must be the case: an alternative explanation would be that there are no feasible substitutes. If the definition of "feasible" includes economic reasons such as cost of substitutes, then, of course, the "weak sustainability" position is at least partially correct. However, the argument becomes slightly more circular as a result.

It needs to be stressed that this problem is more influential in debates of political nature, rather than in scholarly discourse. Most economists are well aware of the limitations of the substitution argument; unfortunately, this awareness does not extend to the broader public. Because resource policies are not determined solely by economists, the problem and its potential impacts are therefore significant.

The problem illustrates nicely why classical economic thought is ill-suited for thinking about the potential and mechanics of resource scarcities. In theory, the substitution potential is limitless — if we assume that substitution will happen if the price of a resource rises too high, and if we assume that the reason why some seemingly scarce resource has not yet been substituted is because it is not yet scarce enough. In theory, such economic thought could indeed "prove" that human economy can continue business as usual for as long as needed: the overall level of consumption stays the same even if the price of some resource rises, as consumers simply consume less of the said resource while substituting either the resource itself or the goods derived from that resource for other resources or goods derived from other resources. Following this line of reasoning to its logical conclusion, one could conclude that we could trade all of our breathable air for woolen mittens and not be worse off, provided we gained enough mittens in return. From the viewpoint of economic thought, resource scarcities pose only uninteresting questions that always have the effectively same answer: we'll substitute when it is economically rational to do so, and business shall continue as usual.

Unfortunately, such generalized answers may well hide what perhaps ought to be the real question concerning resource scarcities and our coping mechanisms: *how the scarcity or the substitutions impact people and society?* On a large enough scale, global economy isn't much impacted by most scarcities, unless some important factor of production whose demand elasticity is low (such as oil) becomes scarce. Even then, the impacts are limited: some sectors lose, while others gain. However, scarcities can have major impacts on individuals and societies experiencing them. A local scarcity that doesn't even register on worldwide news can nevertheless cause wrenching dislocation and even breakup of existing societal structures as previously lucrative jobs vanish or move to another location, perhaps another country. Similarly, while a local or even global extinction of some living species may not be a worldwide emergency, some people in a specific area might suffer greatly from the loss.

The discussion of these impacts will be incomplete if it is conducted only within the framework imposed by mainstream economic thought. Business-as-usualist framework minimizes both human and economic impacts, practically ignoring the former as unavoidable "realities" while smoothing over the latter as just another example of the great, unseen machinery of the economy seeking the stable equilibrium once disturbed.

8.2.2 The problem with pessimism

However, the above critique does not mean that the resource pessimists are correct. Just as economic thought serves to mask questions of impacts, so does the neo-Malthusianism in its doom and gloom. A constant focus on potential global catastrophic risks of resource scarcities, be it climate change, peak oil, global famine, disastrous loss of biodiversity, lack of copper or any of a number of resource constraints touted as potentially catastrophic, turns the discussion of scarcities and their impacts towards large-scale questions that are not immediately relevant to most people on this planet. This should not be surprising, as both the business-as-usualism and neo-Malthusianism spring from the same economic root, where humanity is viewed abstractly as an aggregation of consuming-units that require a specific resource input to live and strive to increase their resource endowment while they live: the difference is that business-as-usualists see the latter trait either as a good thing or at least as an unavoidable part of human character, while neo-Malthusians generally see "greed" as a character flaw that ought to be eradicated.

In its pessimism, neo-Malthusianism also tends to fail to address the questions of scarcity's or substitution's impacts on human society. Just as business-as-usualism answers all resource scarcity questions similarly, that we shall substitute when it's rational to do so, so does neo-Malthusianism: the difference is that of a mirror image, as the pessimists state that some critical resource simply cannot be substituted and our current way of life is doomed as a result. Which scarcity exactly is picked as a herald of our downfall seems to depend mostly on the prevalent *zeitgeist* among Malthus's followers. In the early 1800s, the resource crisis *du jour* was over food supply, in late 1800s, coal, in the early 1900s, oil and copper, and in the 1960s and 1970s, food (second time round). Now, in the early years of the second millennium, the fashionable reason for society's imminent demise seems to be the scarcity of carbon dioxide sinks in the atmosphere (that is, climate change) and/or oil (also on its second round), even though stable oil prices seems to have stifled, for now, the latest burst of pessimistic predictions about the imminent, society-crippling shortage of oil.[2]

While many authors have tried to envision the future societies that may result from failures of substitution — a distinct improvement, it must be said, upon business-as-usualism with its essential *lack* of vision for future — these visions are always eerily similar in their broad outlines: a collapse of global society and, for the survivors, a retreat to simple pastoral communities. It is hard to escape a feeling that many authors in the doom-and-gloom brigade, many of whom also have a track record of railing against the perceived evils of contemporary society, would in fact welcome such developments.

However, history shows that so far these predictions have turned out to be too pessimistic. Arguably, there is a systematic tendency to exacerbate the risks and dangers, both for dramatic effect and because of ideological reasons, just as there is a tendency to underplay any potential issues because of different ideological reasons. Available evidence suggests that there is some reason for cautious optimism: particularly in case of non-discrete resources such as basic metals and minerals, price signals seem to have worked pretty much as business-as-usualists have claimed they would.[3] In the days when Ira B. Joralemon issued his warnings (Joralemon, 1924) about the impeding end of copper, and hence the age of electricity, copper mining was believed generally unfeasible if copper content in ore was below two percent. Today, average copper ore contains just 0.6 percent copper. By and large, the economy and the electric society as a whole have managed to survive, even thrive.

That said, price signals may not always work as simplified theory predicts. For example, Suokko and Partanen (2017) and Fix (2014) note that the price of oil — potentially a crucially important resource, albeit (hopefully) less so in the future — may not ever rise high enough to promote additional exploration and development of

[2] I would like to emphasize in the strongest possible terms that I do not in any way wish to minimize the very real threat climate change and certain other environmental predicaments pose to the wellbeing of humanity and the rest of the living world.

[3] Here, non-discrete resources refer to resources that exist dispersed throughout the Earth in varying quantities and whose extraction and use depends more on technology and economics rather than immutable factors such as geology. Discrete resources, on the other hand, are resources such as (conventional) oil that cannot be produced outside specific productive areas, even with advanced technologies.

alternatives. According to these critical voices, the willingness and ability to pay for a resource set limits to the price of a resource. If the productivity increase gained from the use of the resource is less than the cost of the resource, then the price of the resource may remain low despite there being, for all practical purposes, a shortage of it. Hence, no price signal. This view is at a first sight at odds with the mainstream view that assumes price signals will cause alternatives to be found, but the mainstream view also includes the caveat: *if there is demand for the alternatives in the first place.* Therefore, the mainstream economist can counter that the economic system will adjust to the new reality, and people will alter their consumption bundles accordingly to maximize their benefits. If oil is scarce, people will (so the theory goes) derive utility from activities that demand less oil, as they become relatively more attractive. The same can be said for any resource.

As a result, on a macro enough scale, it seems unlikely that "the economy" or "the society" will falter because of shortages of any one material. Even if one discounts the above counter as mere sophism, the truth is that the world economy is a remarkably resilient system that can adapt to a variety of conditions, even if at a decreased output. While economy's sheer complexity and interconnectedness causes potential vulnerabilities, as the collapse theorist often are wont to point out, the more pessimistic assessments invariably forget that complexity can also increase the resilience of a system. Some of the most complex systems ever encountered, including the Internet and the human brain, are also some of the most resilient. The Internet is famous for the difficulties even intentional attempts to restrict its functionality encounter, and human brains are capable of surviving, with remarkably small impacts, even hemispherectomy, or the total removal of one half of the brain. The vast interconnectedness of the world economy can be a source of weakness, but it can also be a source of strength.

"Proving" the matter one way or the other is impossible, but it is worth remembering that the last large-scale famine in Europe, the Finnish Years of Great Hunger between 1866 and 1868, likely wouldn't have happened in a more interconnected economy (see Myllyntaus, 2009; Newby and Myllyntaus, 2015). As the world economy becomes more and more complex and diverse, the likelihood that shortages of any one resource will cause serious issues are likely to diminish. Furthermore, it is far from certain the current assumptions about Earth's resource limits will hold. To take just one example, even asteroid mining may very well become both possible and profitable in near future due to recent advances in reusable rockets and robotics, as well as due to increasing interest in the closely related mission of deflecting asteroids on potential collision course with the Earth. Success in asteroid mining would effectively mean an end to concerns about the availability of basic and platinum group metals, and likely greatly reduce the likelihood of running out of other minerals as well (Ross, 2001).

On the other hand, even if the society is unlikely to collapse because of a scarcity of some individual resource (or, perhaps, even as a result of shortages in several important resources at once), shortages and scarcities can cause acute problems for individuals, companies, and even for local economies. What *is* certainly possible and perhaps even likely is that the human economy will begin to chafe against the resource limits and, as a result, suffer from reduced growth rates. On itself this might not be a cause of concern, but there is reason to believe that modern, liberal, pluralistic society may not be viable without continuing economic growth (e.g. Friedman, 2005; Suokko and Partanen, 2017). Very often, the particular resource singled out is "cheap" (affordable) and usable energy, which is argued to differ from other resources as no economic activity is possible without it (Ayres and Warr, 2009; Suokko and Partanen, 2017).

If resource limits are indeed a major factor in the prolonged slow growth several rich nations have witnessed lately, the message of this thesis should sound another warning: we shouldn't rely on technology to develop in a way that resource constraints will be circumvented (a topic to which I shall return later in this chapter). However, the resource scarcity argument is not entirely convincing, and it is not clear whether we truly ought to ascribe lack of growth to resource constraints and not to, say, myopic policies (see e.g. the argument about lack of long-term governmental investment in research and development being an important factor, Mazzucato, 2011). What's more, even if resource limits ultimately prove to be the direct or indirect cause of the downfall of the pluralistic-liberal experiment, it seems there is very little we can do to circumvent the limits. For that reason alone, caution might be advised before claiming that resource crises will lead to major societal problems, either indirectly or directly. If the societal problems are indeed manageable through other means, then claims that resource access is *the* defining question will distract from the effort of developing and implementing those other means while providing very little useful guidance on how to expand the resource endowment.

Nevertheless, I'm not arguing that potentially dangerous scarcities cannot possibly exist, and I'm most emphatically not arguing that they shouldn't be discussed. While I think there are reasons to believe that shortages of one or few resources are unlikely to pose severe problems for human civilization, my belief cannot be either proved nor disproved with available evidence. The issue here is that sweeping, pessimistic and somewhat simplistic assessments are not very good guides for coping with scarcities either. As critics of simplistic "environmental footprint" calculations (e.g. Nordhaus et al., 2012; Bass, 2009; Blomqvist et al., 2013; DeFries et al., 2012) have noted, talking about scarcities as global in nature when in fact many of them (say, scarcity of fresh water) are highly local can only muddle the issues and conflate local problems into global predicaments that by their very immensity begin to seem hopeless. Similar problems are bound to arise if we continue to treat scarcities simplistically. To navigate our route in the future, we need to know the terrain ahead in more nuanced terms than "smooth going" or "impassable."

8.2.3 Towards resilience and "what then" questions

However, a more fruitful approach may be in the offing. The last decade and a half have seen a major expansion of so-called resilience thinking (Folke, 2016), where many of the shortcomings of the above mentioned, ultimately reductionist approaches have been addressed. According to Folke (2016), resilience is about persistence, adaptability and transformability of complex adaptive social-ecological systems. With its more holistic focus on answering more practical small-scale questions instead of providing an overarching, reductionist worldview, it offers a possibility for better answers for the more interesting and relevant questions of how individuals, organizations and societies can cope with the challenges of the future — some of which may well include resource scarcities of some sort or the other. Thus, it would seem fruitful to move the discussion away from the unproductive reductionism and "yes we can/no we can't" of the Simon/Ehrlich type debate (Sabin, 2013), and instead start asking practical questions, such as how we as a society ought to respond if a scarcity of some important resource actually threatens some particular aspect of our lives?[4]

This debate is important not just because it is more fruitful than trying to determine whether our society is doomed or not, but also because the paths taken forward can differ significantly in their

[4] Another reason is that it seems close to impossible to get societies to act on potential resource crises unless they actually happen, and effecting major changes without a major crisis seems to be difficult if impossible (see e.g. Scheidel, 2017).

repercussions to our lives and in our society. As I argued above, it seems likely that "the society" or "the economy" will survive future resource crises: the question is, *what kind of society will we have as a result?*

It is all too easy to envision a dystopic future where a succession of resource crises lead to gradual erosion of our democratic, pluralistic systems, to impoverishment of individuals and nations, and even to major wars. Examples of such dark visions abound in just about every resource pessimistic treatise, and they seem to hold a morbid fascination among certain parts of the populace. Undeniably, the risks need to be discussed: given historical trends towards concentration of wealth and power, it seems very possible that economic consequences of resource scarcities simply accelerate the division of our society towards haves and have-nots. However, crises can also be opportunities for positive change, and there is a both a risk and an opportunity of our prognostications becoming self-fulfilling predictions. Thus, in a return to the themes of Essay I, engaging in a deliberate narrative building about the possibilities of a better, more just world for everyone should perhaps be a higher priority for scholars and activists wishing to build something constructive on the admittedly barren ruins of the resource scarcity debate. While I can offer little guidance on exactly what kind of discussions we ought to be having, I can suggest that optimism tends to be more motivating than pessimism. This seems to be the conclusion of resilience research as well.

But what of efficiency?

Another important lesson from resilience research is that resiliency and efficiency are often at odds with each other. As I argued in the Essay IV, increasing the "efficiency" of socio-technical systems (of course, there is a separate and important problem of how "efficiency" should be defined and who gets to define it) usually means optimizing the system for a particular function. This means getting rid of anything that does not immediately contribute to whatever outputs are defined to be the measures of efficiency. The downside is that systems that perform well under expected conditions are often fragile when confronted with unanticipated events (Anderies, 2015; Folke et al., 2010). Efficiency drives also seek to eliminate "slack" — that is, reserves that might be necessary to cope with unexpected developments. Therefore, unless the efficiency metrics are selected just right, a more efficient system is almost always a more fragile one as well.

These issues ought to be considered carefully, since practically all proposals for reducing humanity's environmental impacts and avoiding resource scarcities place great trust on greatly increasing the efficiency of resource use. In just one example, the emission reduction scenarios proposed by Greenpeace together with industry group European Renewable Energy Council propose that total world energy use will actually be significantly *lower* in 2050 than what it is today, even though the world is going to be inhabited by two to four billion more people by then (Korhonen and Partanen, 2015; Partanen and Korhonen, 2016; Heard et al., 2017). Practically all of this reduction is to come from increased efficiency, as the authors promise that the plans nevertheless provide the vastly greater mass of humanity with equal or greater level of energy services compared to today. At the same time, the remaining energy demand is to be met mostly from solar and wind generators. Their very high variability results to a very Rube Goldberg-esque energy system where (so it is envisioned) any single country's daily energy demand is produced sometimes within the country, sometimes hundreds or thousands of kilometers away, yet this massive variability poses no problems even as raw power sloshes freely around the proposed globe-girdling power networks. Nevertheless, the realism of such plans, and just how fragile the extremely lean and efficient energy systems may turn out to be, are not often discussed.

Similar focus with efficiency and very complex systems underlies many other proposed solutions to resource constraints. However, more resilient approaches would promote response diversity (Elmqvist et al., 2013; Hughes et al., 2007; Jansson and Polasky, 2010) while asking critical questions about the limits of efficiency.

8.3 Do scarcities promote novelty?

Another important motivation behind this thesis was to find something useful to say about the potential of *technological substitution*, or technological development to substitute for scarce resources. Even thought this, too, is a question that cannot be satisfactorily generalized from the case studies presented in this thesis, prior literature and my own studies suggest some possible answers.

Among creativity and innovation researchers, there seems to exist a strong tendency to believe that necessity is the mother of inventions, and that constraints and pressures can promote creativity and innovativeness. The implication is that constraints can be a force for good (at least if we define "good" and "innovation" to be equivalent), and that some "proper" level of anxiety will make innovators work harder and produce better results. The implication is optimistic and in line with mainstream economics and business-as-usualism discussed in the previous section: if we face challenges, we will overcome them.

However, as I argued in essays II, III and IV in particular, external forces such as constraints are not very effective in significantly accelerating the pace of technological change. Even though the mainstream economic thought tacitly believes that necessity must lead to innovation, in reality there is no law that states that a scarcity of some key resource will magically cause the invention of a substitute. Technologies are complex recombinations of existing components (including both physical parts and knowledge, see e.g. Fleming, 2001; Arthur, 2007, 2009), and if the components necessary for a given technology do not exist, the financial incentives for inventing that technology matter little.

Theoretically, the incentives could be thought to influence the development of necessary components as well, but in practice this seems to be the case only rarely. After all, new technologies are usually recombinations of previously unrelated components, and innovations, particularly important ones, are by definition somewhat unexpected recombinations (cf. e.g. Schoenmakers and Duysters, 2010). Therefore, in order to speed up the development of technology, the proposed incentives would have to influence the development of often entirely unrelated components. Because no one knows or even expects that just these components will ultimately prove useful in the development of the incentivized technology, it seems unlikely that incentives to develop a technology whose components do not yet exist will prove very useful.

Furthermore, development of new knowledge seems to require some minimum amount of time and effort. If, for example, the problem is in developing long-lasting parts or compounds, then some time will be needed to gather enough experience to know whether the new idea indeed outperforms the old one. No amount of incentives can greatly reduce the time needed to gather necessary experience. As one of the fathers of modern rocketry, Wernher von Braun, reportedly quipped, "crash programs fail because they are based on theory that, with nine women pregnant, you can get a baby in a month."

In the case studies presented here, there is little evidence that scarcities caused innovators to come up with novel ideas. Rather, what happened was that already developed ideas and technologies, whose components were widely available, were finally taken into use. As I argue in Essay I in particular, this is more an argument for good preparation rather than creativity flourishing under adversity. If these tendencies are generalizable, and I believe they are, then the implication is that necessity is not the mother of inventions: however, it may be the mother of *inventors* (see also Essays II and III).

What this means is that inventions are most likely going to be invented and taken to use as innovations without any undue delay even without scarcities to prod the developers along. However, while inventions are unlikely to be invented just because of a scarcity, scarcities and constraints can influence *who* exactly develops and adopts a specific technology. The Outokumpu case illustrates this dynamic: absent an electricity shortage, *Outokumpu* would have been unlikely to become the developer of the flash furnace. However, the Canadian Inco would've developed the furnace nevertheless, and in a counterfactual world where copper smelters would've been unable to purchase Outokumpu furnaces, some other copper manufacturer would've almost certainly adopted a similar design. The adoption of flash furnaces might have been delayed by some years, but most probably not significantly. Similar lessons can be learned from the briefer case study on jet engine design. Ideas whose time has come are rarely long delayed, which is why simultaneous discovery is the norm in science and technology (Ogburn, 1922; Gilfillan, 1952; Brunk, 2003; Cole, 2004; Singh and Fleming, 2009; Lemley, 2012; Sarafoglou et al., 2012) and why even true geniuses like Einstein were unlikely to significantly speed up the accumulation of knowledge (Boughn and Rothman, 2011). In brief, scarcities can impact the landscape of technological change and its details, but are unlikely to have significant positive effects. This finding is broadly corroborated by earlier case studies from Roediger-Schluga (2004) and Hoogma (2000).

This ought to be sobering news for those who place their faith in humanity's capability to invent new technologies in a timely fashion to circumvent resource scarcities and their effects on society and individuals. Even though I generally appreciate the optimism of the so-called cornucopians, who believe in perpetual growth and improvement of humanity (Sorman and Giampietro, 2013; Sabin, 2013), I must advise caution: there are no guarantees whatsoever that technologies will be invented just because their invention would be very profitable or beneficial. If new technology is not ready for prime time, it is unlikely any sort of scarcity will significantly speed up its deployment. Furthermore, attempts to push half-baked technologies into use all too often end in frustrating failures, as the history of technology has numerous times documented. To a large extent, technology marches to a beat of its own, and expecting that societies are able to hurry it up can be a dangerous delusion. In our innovation-crazed society, this nevertheless seems to be the general expectation. Even the traditional environmental movement that used to be skeptical of "techno-optimism" is these days tacitly or even explicitly assuming that technologies required for their preferred solution to climate change and energy poverty, a global 100 percent renewable energy system, will be developed just because developing them would be very profitable and beneficial (see e.g. Korhonen and Partanen, 2015; Partanen and Korhonen, 2016). The fact that many of these technologies are arguably still to be invented seems to raise no eyebrows among those who argue that because rapid advances have been observed in an entirely unconnected field, information technology, similar leaps and breakthroughs must be feasible in energy technologies as well if only we want them badly enough.[5]

8.4 The social construction of scarcity and technologically feasible

But what, then, is a "feasible" technology? Again, the maddening conclusion of my study is that there are no clear criteria with which to judge whether some technology is ready to adoption (or more widespread use) or not. Consequently, there are no clear criteria of assessing, before the fact, whether a scarcity of some key resource can be circumvented with (technological) substitution. There may be good reasons to believe this will happen in certain cases, most particularly when the resource in question is non-discrete or there is clear evidence that alternatives are available. However, in most cases, all *ex ante* assessments are likely to be little more than educated guesses. Some resources are likely to be more difficult to substitute than others, and certain resources, such as breathable air, are likely to be unsubstitutable in practice. Several authors have claimed that energy is a "master resource" that cannot be practically substituted (e.g. Ayres and Warr, 2009; Sorrell, 2010; Trainer, 2014; Suokko and Partanen, 2017), and it seems likely that scarcities of useful energy supplies are likely to have greater (and perhaps

[5]The standard refrain from these modern techno-optimists is that their ambitious plans require only "existing" technologies. A more careful study of the plans presented, however, quickly shows that the definition of "existing" can be very flexible: the general tendency in the more optimistic energy plans seems to be that if a technology has been tested on a laboratory scale somewhere, it counts as "existing" — even though it is well known that the true idea of technology's feasibility is obtained only through deployment and use. See also a review by Heard et al. (2017).

more certain) impacts than most other scarcities (Sorrell, 2010).

However, the two important things this thesis has taught me are that what is a feasible substitute for a scarce resource — indeed, what is a scarcity — is a highly political question, and that what matters the most may very well be the *perceptions* of scarcity and feasibility, not some objective, measurable truths. Furthermore, these perceptions are interlinked: what is perceived as technologically feasible depends heavily on perceptions of economic and political feasibility, and these perceptions in turn are affected by what is seen as technologically feasible. In other words, concepts such as "scarcity" and "technologically feasible" are to a large extent social constructions.

8.4.1 The mental rebound effect

The essays I and II in particular offer examples of how "technologically feasible" and "scarcity" are constructed and maintained. In the first case, there are reasons to believe that the nickel scarcity that many contemporary and current observers believe hampered the German wartime effort to develop jet engines was at least in part maintained because the jet engine designers were able to come up with satisfactory nickel-saving designs. Given the nickel resources available, the projected "worst case" demands of the jet engine program, and the importance of the latter, it is very hard to believe that loosening the nickel constraints would have been impossible. After all, the traditional aeroengine industry demanded significantly higher quantities of nickel for engines of greatly inferior performance, and Germany in fact ended the war with greater nickel reserves than at the beginning of the war. However, there was little reason to loosen the constraint as long as the jet designers made do with what they had — and they made do with what they had because they perceived nickel was scarce.

In the second case, Outokumpu's perception of energy scarcity was most likely influenced by its perception of the feasibility of flash smelting. As detailed in the Essay II, a contemporary observer could hardly have faulted Outokumpu if it had simply pressured the government to loosen the energy restrictions in one of the several ways possible. However, perception of scarcity was maintained because the new technology didn't require Outokumpu to pressure the government for better energy access.

These two cases illustrate a dynamic that can actually perpetrate the scarcities *because* more resource-efficient technology is developed or taken into use as a result of perceived scarcity. The dynamic might be called the "mental rebound effect" after a similar nonintuitive but well-documented dynamic. The rebound effect refers to a reduction in expected resource savings due to a new technology, because of various behavioral responses (Sorrell, 2010; Magee and Devezas, 2016). In energy economics in particular, the rebound effect is known to eat into expected gains from energy efficiency, since more energy efficient tools and appliances are cheaper to run and therefore used more often, sometimes in applications where they were not economical to use previously.[6] The mental rebound effect works somewhat similarly: attempts to relieve the scarcity by developing or adopting more efficient technologies or behaviors lessens the pressures (financial or political) to ease the scarcity through other means. This effect seems useful to help explain why the German jet engine designers felt the nickel constraint so pressing, despite Germany having arguably more than ample nickel reserves for the program of such importance, and why Outokumpu did not do more to alleviate the energy scarcity through political means, even though it did not hesitate to throw its weigh around in scarcities that were almost certainly far less serious. The mechanism can also provide part of the explanation for the observation made by Suokko and Partanen (2017), that price of a scarce resource may not in practice rise enough to stimulate a hunt for new sources or new substitutes. If the society seems to be coping with the scarcity, why should political decision makers, for example, bother to channel funds into research for substitutes?

If the mental rebound effect dynamics are generalizable, and I believe they can be to some extent, then attempts to cope with scarcities by increasing the efficiency of resource use may be less successful than it would appear at the first sight. This problem affects mostly individuals, companies and industries at worst, though: from the viewpoint of the economy or the planet as a whole, being more efficient in our resource use is certainly desirable. Even if rebound effects are likely to eat some of the savings made, and even if the scarcity may not go away if the greater efficiency persuades the gatekeepers to perhaps even tighten the resource availability, doing more with less is a good thing. However, as individuals and as researchers, we shouldn't trust that a scarcity will be eased if we learn to be more efficient with the given resource. What may equally well happen is that the scarcity will persist, perhaps even worsen.

[6]This behavior is also often referred to as the Jevons paradox, after the economist who was the first to describe it in 1865 (Jevons, 1865).

8.4.2 Other examples of socially constructed scarcities

While the case studies presented in this thesis do not by themselves allow us to generalize that scarcities are typically socially constructed, it is remarkable that two very different cases show signs of similar dynamics. Furthermore, earlier studies (Hoogma, 2000; Roediger-Schluga, 2004; Yarime, 2007) have also noted that constraints, perceptions of technological feasibility, and politics are very often intertwined. For example, the 1990s California Zero Emissions Vehicle mandate, requiring a percentage of cars sold in California to be electric by 1998 and studied in detail by Hoogma (2000), is generally believed to have been adopted largely because of optimistic remarks about the feasibility of electric cars made by the then-CEO of General Motors at an auto show in 1990. For some time, electric cars seemed feasible largely thanks to the mandate. However, the mandate was eventually loosened and then effectively dumped once it became clear that car manufacturers were not only unwilling but also (generally speaking) incapable of delivering required advances in technology. Hence, a constraint was loosened through political action and pressure from car manufacturers, once meeting the constraint by technological means proved difficult and expensive. Similar dynamics were observed in the Austrian chemical industry by Roediger-Schluga (2004), and it is entirely according to this theory that in response to the recent diesel car emissions cheating scandal, many European governments proposed to *loosen the emission standards* rather than to penalize the cheaters.

What these cases seem to suggest is a theory of interplay between constraints, technology, and politics. A single-sentence summary might run thus: *Industries weather scarcities and constraints through the path of least resistance, which can include political action commensurate to the political importance of the industry, as well as technological change.* Trivial as this theory is, it may be worth keeping in mind, as stringent constraints to e.g. carbon dioxide emissions are being proposed to help avert dangerous environmental consequences. These are laudable aims, but it seems that many proposals and those proposing them assume that the affected industries will quietly adapt to the new rules. In reality, the industries might well respond by attempting to undermine the constraints placed on them, and politicians may be hesitant to enforce the rules in the first place for the fear of their impacts on important industries.

The public discussion about EU emission trading scheme illustrates this disconnect: I have personally witnessed numerous occasions where environmental activists and Green politicians have, in effect, argued that the availability of low-carbon energy has little connection to what is a politically feasible carbon emission target. However, if low-carbon energy is scarce and/or expensive, then the costs of meeting more stringent targets will increase, with attendant detrimental effects to affected industries, some of whom may be major sources of tax revenues and employment. To a disinterested observer, it would therefore seem strange if the availability or cost of low-carbon energy would not have any effect on the stringency of measures that the politicians are willing to endorse.[7]

A corollary is that not only technologies but also *perceptions* of what is technologically feasible can be very highly political — and conversely, that politics have great influence on what we perceive as feasible. It's long been acknowledged that visions of the future can have great impacts on the society, and it is no accident that interest groups are prone to exhibiting their own visions of technological change in a plethora of future-oriented reports and scenarios. The history of the last 200 years has conditioned us to expect that technologies in our lives will change: from that expectation, it is a very short distance to expecting that technologies will change in a manner that happens to validate whatever preconceptions and political leanings we may hold. At best, or worst, these perceptions of feasibility can become self-fulfilling prophecies.

8.4.3 Constraints or scarcities?

This dynamic also sheds some light into what oft-mentioned "constraints" actually are. In short, they are the *boundaries of what is perceived possible* (cf. Cilliers, 2001). As perceptions of possibility change, so do the perceptions of what factors constrain the possibilities. An interesting question, however, is whether perceived constraints to what is possible and scarcities of natural resources are the same or even similar phenomena. Constraints are a topic in creativity literature, where numerous studies have explored the relationship between constraints and creativity (e.g. Ward, 1994; King, 1997; Goldenberg et al., 2001; Moreau and Dahl, 2005; Stokes, 2014). In theory, scarcities of natural resources can perhaps appear to individual technologists in the same manner as other constraints, but actual research in this topic remains scarce. Furthermore, it seems likely that natural resource constraints can be more unyielding, at

[7]It should be noted that there are reasons to suspect that much of this rhetoric is motivated by the long-standing opposition to nuclear energy. If the environmental organizations or Green politicians admitted that it matters how much low-carbon energy is available, then their calls to shutter nuclear power, by far the largest single source of low-carbon energy in Europe, would suffer a serious blow.

least in the short term, than some other types of constraints, and less amenable to reconstruction.

8.5 The different kinds of constraints and scarcities

Finally, my research has led me to strongly oppose the simplistic or reductionist views of constraints and scarcities. Even though it is possible to reduce all scarcities to fundamentally economic ones, doing so is not necessarily wise. As I argued already in Essay II, such reductionism risks abstracting out many important details and differences, while discouraging further discussion.

To that end, and following the exhortations of other scarcity researchers (e.g. Lähde, 2013), I outline here some ways to make sense of scarcities and constraints and to differentiate between what are, in my mind, important distinctions between different types.

8.5.1 Quasi-scarcities, power, and self-perpetuating scarcities

To make more sense of the various types of constraints and scarcities that technologists and societies actually face, it is beneficial to follow Daoud (2007; 2011) and make a distinction between relative-, quasi-, and absolute scarcities. Relative scarcity generally refers to scarcity in mainstream economic sense, where many "wants" compete for a limited amount of "means". In contrast, absolute scarcity denotes a situation where some, usually essential resource ("need") is simply not available for some reason (Raiklin and Uyar, 1996). An useful distinction between the two is substitutability (Baumgärtner et al., 2006): if a resource can be substituted or allocated differently, then the scarcity is relative; if not, then the scarcity is absolute.

Aside from these two extremes, of particular importance for discussion about scarcities in society is the concept of quasiscarcities, derived from Amartya Sen's work on causes of famines and in particular from his concept of *entitlement* (Sen, 1982). While research explicitly linking Sen's entitlement approach to resource scarcities other than food seem to be limited to a treatment of water scarcities (Anand, 2007), Daoud's (2007) notion of quasiscarcity has fruitfully developed the concept into a "scarcity neutral" direction. In a quasi-scarcity, enough resources exist on the system level, but lack of entitlement, or access to the resource, prevents individuals at a lower level from obtaining the resource (Daoud, 2011, p. 43). The distinction from relative and absolute scarcities is important, as the concept shifts the analytical focus from a fixation on supply and allows us to bring both power relations and changing technology to the discussion.

Individual's lack of sufficient entitlement is often a symptom of insufficient power in relation to those who control access to the resource. Amartya Sen and others (e.g. Sen, 1982; Blaikie, 1985; Boyce, 1987; Daoud, 2007) have argued that in case of food, lack of democracy (essentially, lack of power) has been a root cause of many famines around the world, although, as is only to be expected in such a complicated phenomena, democracy is no panacea against famines (nor, presumably, against other scarcities) (Rubin, 2009). Even with the obvious qualification that lack of entitlement does not explain all resource scarcities, it is clear that examining power relations can greatly help in explaining why some resources are scarce and why some shortages play out the way they do. As just one example, regulations that "artificially" limit the use of some resource can be thought of as quasi-scarcities: power relationships between the users of the resource and the regulator can explain the ensuing regulatory policy.

An important feature of quasi-scarcities that result from power imbalances is that they may be particularly prone to the mental rebound effect discussed earlier. If a resource exists in principle, but its use is for some reason restricted, the users are likely to come up with ways to conserve the resource and use it as efficiently as possible. If this enables the users to cope with the scarcity, there will be less pressure to ease the restrictions for the use of the resource. This phenomenon is particularly apparent in regulatory realm, where the tightness of environmental regulation is often related to what is perceived to be feasible from a technological viewpoint (see in particular Roediger-Schluga, 2004).

The most troubling implication for possible self-perpetuating scarcities involves efforts to reduce world poverty. Those now suffering the most from scarcities of some essential resources are unlikely to gain much more resources unless they can also control the resource endowment. Absent the power to do so, being more efficient in resource use is just as likely to lead to decreasing resource endowment as it is to lead to a material improvement in living conditions. Thus, the power relationships and their study should have a higher priority in studies of poverty and scarcities among the poor — much as Amartya Sen originally suggested.

8.5.2 Scarcity of supplies or scarcity of sinks?

To help explain differences in societal response to scarcities, we can also differentiate between scarcities of supplies and scarcities of sinks. A scarcity of supplies is what most people intuitively think about when thinking of scarcities. It refers to a situation where some resource that humans require either directly (e.g. food) or to create some economic good — in other words, a factor of production — is in short supply. However, modern-day scarcities are increasingly of a slightly different type: a scarcity of sinks that process the usually unwanted byproducts of the production process. Local scarcities of sinks to industrial waste are a phenomenon as old as the industry, and perhaps the most pressing environmental problem of our age, climate change, is a direct result of an increasing scarcity of atmospheric sinks for safe disposal of gaseous carbon dioxide.

Whereas scarcities of supplies can manifest themselves as a direct, physical result of some resource simply not being available for use, it is very rare for scarcities of sinks to become a problem so directly. Sinks are usually shared, more or less open access resources that can be exhausted (or, perhaps, clogged) by unscrupulous users maximizing their own benefit. As such, scarcities of sinks tend to arise as a result of some scheme devised to manage the use of these commons, such as environmental regulation.

The end result is nevertheless ultimately similar to a scarcity of supply. One could perhaps argue that the difference is that the management scheme generally causes a scarcity of permits for waste disposal. (However, many scarcities of supply present themselves as scarcities of permits as well: note, for example, fisheries management.) Because permits are social constructions and not physical facts, scarcities of sinks are likely to be regulatory quasi-scarcities. Due to their socially constructed nature, it also follows that perceived technological possibilities have much greater impact on scarcities of sinks. A pertinent example is humanity's utter failure to enact strict enough carbon dioxide emission limits, largely because carbon-rich fossil fuels still constitute some 85 percent of global energy supply, lack of energy is perceived as inconceivable from a societal viewpoint, and the alternative sources are not growing rapidly enough. As a result, at the time of writing there is no truly pressing scarcity of societal or regulatory permits to dispose these gaseous wastes into the atmosphere, and there are good reasons to believe that such pressing scarcity may not materialize before and unless alternative energy sources have already nearly toppled fossil fuels from their pedestal.

In short, while much of the literature about scarcities has so far dealt with scarcities of sources, it may well be that it is the scarcities of sinks that pose the most important yet intractable challenges. It may also be worth remembering that strategies and assumptions about, say, the role of technology may not be completely applicable to the question of sinks, if the said strategies and assumptions were developed in a context of sources.

8.5.3 Local or global scarcity?

Various environmental footprint calculations purporting to show the "overshoot" of humanity's resource use are the staple of resource pessimists' argument. The danger, according to ecological footprint calculators and those suggesting the humanity to abide by closely linked but more nuanced concept of "planetary boundaries" (Rockstrom et al., 2009; Steffen et al., 2015), is that for certain key resources (supplies or sinks), the Earth system either has or may have boundaries that, if crossed, could force the planetary system over a tipping point and force it to function in a fundamentally different manner from the past.

However, as numerous critics of these calculations and the planetary boundaries approach have pointed out, trying to devise measures for global footprint tends to conflate local and global scarcities (Nordhaus et al., 2012; Bass, 2009; Blomqvist et al., 2013; DeFries et al., 2012). Such conflation can muddle the thinking about scarcities and should be approached with caution. For example, global freshwater use (one planetary boundary in Rockstrom et al. (2009)) tells hardly anything useful about water management: limiting water use at places where it is abundant will do very little to ameliorate scarcities elsewhere (Nordhaus et al., 2012). Unless the resource in question is truly global, and perhaps also fungible, only local scarcities are generally meaningful to people. Of the nine planetary boundaries identified by Rockstrom et al., Nordhaus et al. (2012) identify only three — global climate system, ocean acidification, and ozone depletion — as being truly global in nature and having "strict" boundaries that can be set with reference to science alone (and even for these boundaries, this latter assertion is highly debatable). The others are mostly regional or local, and even severe depletion of the resource at some locality will do little for its availability elsewhere. Those of us who were wondering, as a child, why we were being told to empty our plates because children in Ethiopia were starving can readily understand the difference.

The discussion about whether the planetary boundaries approach is flawed or not is beyond the scope of this paper. However, the critiques are valuable in pointing out that local and global scarcities can be very different things and that global limits may be of very little use in actual policy-making. As Nordhaus et al. note, by conflating local with global scarcities, we might end up advocating (and some organizations are in fact advocating) that fertilizer use in farming ought to be reduced globally due to concerns about the environmental impacts of overuse in the rich countries. However, many poor farmers would benefit greatly from increased fertilizer availability, with little negative environmental consequences.

As hinted in the above section, global scarcities are generally scarcities of sinks and need to be addressed through some scheme that can manage the commons. On the other hand, for local and regional scarcities, the pertinent questions are likely to be whether the trade-offs between human welfare, environmental protection, politics and economic activity are acceptable in specific cases at specific times.

8.5.4 Time dimension?

Finally, the impact of scarcities on people and societies depends heavily on the time dimension. On sufficiently long timescales, the mainstream economic theory holds: the economic system will adapt and scarce resources will be substituted with non-scarce ones, one way or other. However, it should be kept in mind that one of the very possible mechanisms is the disappearance of human species from the Earth. No wants would also mean no scarcities.

The problem, poorly answered by both resource optimists and resource pessimists, is that many scarcities can look very different and have very different impacts depending on the time dimension we choose to adopt. The resource optimists are generally correct that in the long run, scarcities *will* be overcome (with the abovementioned caveat), but have little to say about how to help people and the environment that are distressed right now. On the other hand, if the starting assumption is that trying to cope with resource scarcities is futile and we are going to see a considerable simplification of lifestyles anyway, then attempts to ameliorate the local, short-term effects of scarcities will also begin to look like needless luxury.

Furthermore, unless the time dimension is explicitly considered, discussions of scarcities and constraints tend to collapse in confusion as people can talk about quite different impacts, probabilities and coping strategies. While my conclusion is that scarcities and constraints are unlikely to lead to the development of technological substitutes in the short term, a longer-term effect cannot be ruled out — though it also cannot be relied upon. There is considerable body of evidence suggesting that credible *anticipation* of a scarcity can spur the development of alternatives (see Kivimaa, 2008), and it doesn't seem too far-fetched to assume that many scarcities the pessimists believed inevitable were avoided at least in part because of early warnings. Possibly the most encouraging example, and one of the few where a global scarcity of sinks was efficiently addressed, is the timely decision to end the use of ozone-destroying CFC compounds in the 1980s, before the ozone layer was seriously harmed.

However, the longer the timespan, the greater the uncertainties. Even though it is certainly *possible* that technological substitutes to various pressing scarcities can be developed, and the past history suggests that many substitutes will be developed, relying on technological change to solve the scarcity problem in any specific instance is more or less a gamble. When the stakes are low, such gambles may well be acceptable; if the stakes are high, as is the case in the climate question, gambling is reckless.

Long horizons also do little for the people that are suffering from scarcities right now. People without adequate supplies of fresh water, or those laid off because a regulatory constraint made a factory unprofitable, are not materially helped by promises of better technology later. If the only responses to their questions are assurances that the great invisible hand of the market will eventually restore the balance, or even worse, that the problem is in their behavior or expectations and therefore not worth even trying to solve, it should not be wondered if the said people become suspicious of the motives and the goodwill of those proposing such "solutions". Scarcities will be inevitable; what matters is how we, as a society, treat those who suffer from them.

Finally, timing matters in another sense. Existing research into the determinants of eco-innovation — that is, constrained innovation — suggests strongly that while regulatory constraints can have positive effects and stimulate ingenuity, their timing needs to be just right (Mickwitz et al., 2008; Kemp and Pontoglio, 2011). This thesis and in particular the Essay IV have provided some theoretical reasons, drawn from the theory of innovation as recombinations (Arthur, 2007, 2009), why this is so. Unless the new technology is almost ready to be taken to use, constraints are unlikely to stimulate its development. In many cases, strict constraints are then likely to lead to non-optimal outcomes, at least from the innovation point of view.

Chapter 9

Implications for theory, practice and further research

9.1 Introduction

This last chapter before the bibliography provides the summary of the findings of this thesis. In the following sections, I will summarize the implications of my research, including a brief section of implications for managers. A discussion of possible further research directions ends the chapter and the thesis.

9.2 Main implications

9.2.1 Necessity may be the mother of inventors, not of inventions

While the nature of this study precludes strong generalizations, perhaps the most important rule of thumb that could be learned from the story presented here is that scarcities and constraints can sometimes spur innovation and lead to "ingenious" solutions (i.e. solutions that are better than expected), but that we should not rely on it to happen. Since the expectation that constraints will inevitably spur constraint-conquering innovation rests at the core of the optimistic, neo-classical assumption of resource scarcities being overcome through substitution, this study is therefore a potential arrow in the quiver of heterodox economists and those who argue against the mainstream economic thought in this matter. Nevertheless, the study also recognizes that scarcity signals (that is, constraints) can and do influence technological change.

Constraints just do not seem to be very effective in advancing or accelerating technological development as such, and inventions whose development had been spurred by constraints would most probably have been developed anyway. Finally, and most importantly, *there are no guarantees that a technological "solution" to a particular constraint exists in the first place,* or if it exists, will be found and implemented in time. Nevertheless, constraints can make a great difference in *who* makes these developments, even if there is less influence on *when.* As we argue in essay I of this thesis, necessity may not be the the mother of *inventions,* but it may be the mother of *inventors.*

Why? As noted above, the question of constraints and innovation in organizations has been subjected to repeated inquiries within the field of organization studies. However, research findings have been seemingly paradoxical, with constraints being seen both to help and to hinder organizational and individual creativity and innovativeness (e.g. Rosso, 2014). The essays II and III argue that these conflicting research findings may be partly explainable by controlling for an important, hitherto underresearched variable - the "prehistory of innovation" or the qualities, history and present state of technology (or task) under development in cases where the effects of constraints have been researched. I argue that individual companies may not have much influence or control over the development of complex technologies, which are typically composed of numerous component "parts" [1] and whose development requires the mastery of many different natural phenomena. Unless these components are sufficiently available to the individual company, it is unlikely that the development effort will succeed. Unfortunately, knowing in advance whether a particular development project requires components not yet available may be difficult, if not impossible — because it is difficult to know in advance what components will be needed. For similar reasons, significantly accelerating the availability of required component parts may also be difficult in practice, precisely because knowing in advance which parts prove useful will be difficult if not impossible.

All this suggests that in the short term, constraints can accelerate technological change mostly through accident: if there is a technology almost ready to be taken into use (that is, if its "component parts" are widely enough available), then constraints can provide

[1] These "component parts" may be actual physical components, or they can represent more intangible knowledge, e.g. knowing of and understanding suitable natural phenomena.

the impetus necessary to push it into use. This is likely to apply both to constraints arising from "true" lack of some resource or an option, and to regulatory constraints limiting the use of some resource. However, it is important to note that these conclusions come with two important caveats. First of these is that the acceleration of technological change is defined here to mean the development of unexpectedly good innovations. "Technological change" in traditional science and technology studies sense is a neutral term and does not imply any directionality; hence, any change in technologies in use counts as technological change, whether it increases or diminishes well-being or possibilities. Defined in this manner, constraints and scarcities are almost certain to result to *some* technological change, and the term should not be mixed with the "accelerated positive change" considered here.

Second, none of the above should be construed to mean that constraints do not influence technological change in the long run, as this they undeniably do. However, what is "short term" or "long run" depends — again — heavily on the technology in question. Some technologies, such as consumer electronics, have shorter "natural" life cycles, while others, like energy infrastructure or process machinery, last longer until replaced. Therefore, lessons learned from one field of technology cannot always be applied directly to other fields. All in all, this thesis argues that the nature of technology matters, and that better "technological literacy" might help us to make the societal decisions we need to make.

9.2.2 A look at constraints as constructs

On what is perhaps a more positive note, constraints seem to be at least partially social constructs. The essays II and III in particular argue that constraints are in reality highly malleable to other needs and purposes, and may in fact be at least to some degree *post hoc* constructs used to justify a particular course of action. In this sense, what people believe to be feasible directly defines what they believe to be infeasible, as well.

Prior research in constraints has been largely focused on externally imposed constraints or assumed constraints to be external and beyond influence of the group actually working to overcome them. Although some recent research (cf. Lombardo and Kvalshaugen, 2014; Rosso, 2014) has begun to examine how the research and development teams experience the constraints, this thesis is to my knowledge the first study to look into how constraints become constraints in the first place, and how they remain such. I therefore expand upon research by Rosso (2014) and others, who have looked at the role group dynamics play in whether constraints inhibit or enhance team-level creativity, and study how group (both in-group and out-group) dynamics matter for constraint formation and permanence. This part of my research suggests that perceived constraints tend to be perpetuated through shared beliefs and technological frames (cf. Orlikowski and Gash, 1994; Kaplan and Tripsas, 2008) shared within the community of practitioners. These shared frames make the actors re-enact the constraints and may lead to a situation where there may no longer be an actual reason for a constraint, but that there remains a perception of one. Importantly, what is perceived as technologically or economically feasible has a major effect on what is, in turn, perceived as a constraint limiting this feasibility. The causal effect therefore seems to run both ways, instead of simple explanations where constraints limit what research and development teams (for example) believe feasible.

Taken together, the first two findings have important implications for both management of organizations and societal policy. If technology cannot be relied upon to develop in a way that effortlessly mitigates resource scarcities without ill effects for our wellbeing, then there is more need for policy actions that either mitigate the scarcities or mitigate their effects. Quite possibly, much of the current economic thought needs a rethink, particularly when it comes to more liberalistic laissez-faire notions of economy. Since it may be infeasible for individual firms to develop substitutes on demand, it is also possible that the role states play in economic arena needs some rethink along the lines of Mazzucato's "entrepreneurial state" model (Mazzucato, 2011). Regulatory debates may also benefit from broader understanding that constraints do not, in the short term and as a rule, give rise to completely novel technologies. Constraints can instead give boost to almost ready combinations, and such emerging technologies may be sometimes predicted with some accuracy. Thus, assessing the likely effects of constraint-tightening regulation should include assessment of those technologies "bubbling under" at the time.

However, the findings also suggest that constraints can be challenged and possibly renegotiated. If a technologist says something cannot be done, there is at least some chance that the statement is motivated more by social convention or other non-technological reasons, and may prove indefensible in the long run. One should therefore examine carefully the assumptions behind such statements, and note that if the underlying assumptions change, the predictions are likely to change as well (see essay II in particular). That said, I wish to emphasize that *most of the time* experts are correct and sincere when they state what is and what is possible in their own field: public debate has already seen far too many glib dismissals of expert opinion as mere outdated "inside the box" thinking, and I have no desire to provide more ammunition for dilettantes. Expert opinion matters, and experts are more often right than they are wrong — and when they are wrong, they are only rarely completely wrong.

9.2.3 A critique of "storytelling bias" in case studies of innovation

If constraints and scarcities only rarely lead to innovative breakthroughs, why do we nevertheless tend to believe they do? This thesis suggests that a possible reason lies in what I call "storytelling bias" in case studies and popular accounts of innovation.

In brief, this bias results from fundamental human tendency to perceive the world through stories and narratives. Some research even suggests that humans are fundamentally storytelling animals whose brains are hard-wired to think in terms of narrative (Young and Saver, 2001), and researchers generally agree that our culture encourages the telling of stories instead of just collections of facts (Roeh, 1989). This bias for storytelling is particularly pertinent when the aim is to craft persuading stories designed to argue for or against something, because people unconsciously expect to find certain characteristics in a "good" and persuasive story. Typically, such persuasive stories include elements such as plot that, after trials and tribulations, ends in a triumph of good over evil. In effect, through birth and culture, we are attuned to see stories everywhere, and even unconsciously select and alter the facts to make what we observe fit better into a narrative format. Because all narratives have to necessarily omit some details, it is possible and even likely that unconscious biases result to us cutting out those details that do not fit into story format.

Stories we tell to each other about innovations are no different. Typical to this tradition, and indeed central to the capitalist ethos particularly in the United States, is the emphasis on singular hero-inventors and their struggle against the odds (Lampel et al., 2014) that results to singular inventions, embodied by patents and patent priorities. This narrative has shown its persistence, even though most research agrees that invention and innovation are collective processes and simultaneous discovery by multiple inventors is the norm, not the exception (Lemley, 2012; Ogburn and Thomas, 1922; Sarafoglou et al., 2012; Singh and Fleming, 2009). Although historians of technology in particular have begun to criticize these conventions (Edgerton, 2004, 2010, 2006), we still tend to prefer a good story over a thorough factual account, if only because accounts of things happening make for dry reading.

And what makes for a better story than the classic "through adversity, to stars" plot line? Narratives of resource-scarce innovation fit squarely into one of the most celebrated and repeated formats for a story we have: they typically include a threatening problem that is solved by an ingenious inventor harnessing the magic of science and technology. The inventor is then rewarded, and life returns to normal once again. We like to read success stories such as these, even when — as essay I attempts to show — the facts are at best open to alternative interpretations. However, since success stories such as those examined in essay I are more likely to become widespread, research into resource-scarce innovation (and potentially, other kinds of innovation) may very well suffer from in-built selection bias when it comes to available case studies. After all, failures are only rarely reported, and even more rarely studied in detail.

9.2.4 A re-imagining and an extended history of a radical innovation in post-war Finland

Besides these theoretical developments, this study also answers to the already noted, almost omnipresent call for longitudinal studies of how constraints and scarcities impact innovation. Furthermore, the innovation in question is undoubtedly a radical one: flash smelting greatly increased the energy efficiency of copper smelting and became the dominant method in copper production, in addition to being adapted for other metals as well. Not only organizational scholars but also science and technology studies should benefit from having one more thoroughly researched case at their disposal.

In addition, this study and particularly its essays I, II and III are an example of recent trend of using historical methods in organization studies (Clark and Rowlinson, 2004; Rowlinson and Hassard, 2013; Rowlinson et al., 2014b,a; Maclean et al., 2015). This thesis is more at home in this emerging research tradition, also known as "historical turn" in organizational research, and therefore not a study of history in a traditional sense. However, I have tried to follow the conventions of historical research rigorously enough to entertain a hope that my work may be useful for technology and economic historians as well. The story of Outokumpu and how it came to develop flash smelting during the post-war "energy crisis" (Frilund, 1961; Seppinen, 2008), even though it arguably had other options at its disposal (essay III), extends the research on post-Second World War economic history of Finland and the prior histories of Outokumpu (Kuisma, 1985, 2016) and flash smelting (Särkikoski, 1999). This post-war period has recently seen increased interest among scholars of Finnish history (Seppinen, 2008; Kallioniemi, 2009; Rautkallio, 2014; Malinen, 2014; Uino, 2014; Holmila and Mikkonen, 2015; Joukio, 2016) and my work can be seen as an extension of these studies.

In particular, my study looks at the alternatives to what has sometimes been presented as almost inevitable march of progress culminating in Outokumpu's fortuitous discovery of flash smelting. The archival and other study undertaken for this thesis strongly suggests that Outokumpu, as an important state-owned company heavily involved in extremely important war reparations deliveries (Rautkallio, 2014; Kuisma, 1985), could very well have twisted the arm of the Finnish government to either help it overcome the electricity constraint, or to provide it with foreign currency and import licenses necessary for more reliable alternative: coal. That these options were, by all evidence, not even seriously discussed may be interpreted as one instance of the "war reparations spirit" said to have imbued the Finnish economy at the time (Matomäki, 2014). However, an alternative reading is that flash smelting was simply a technology whose time had come, and Finland was just a place where the technological readiness and a need happened to coincide. In fact, Outokumpu technically speaking lost the race to develop flash smelting, and it was only a combination of circumstances that made the "Outokumpu method" a dominant one in world's copper smelting (essays II and III). Acknowledging these facts does not diminish the credit Outokumpu and its managing director Eero Mäkinen must receive for taking the significant gamble with the new technology, however.

9.2.5 What options the technologists have when confronted with constraints?

Finally, the essay IV of this thesis develops a theoretical framework for understanding the decisions "technologists" (that is, people empowered to make decisions about technology) make when confronted with various types of constraints. Building on one hand upon Daoud's distinction between relative-, quasi-, and absolute scarcities (Daoud, 2007, 2011), and on the recombinatory theory of technology (Fleming, 2001; Arthur, 2007, 2009) on the other, I develop a model that helps us to understand why some resources and resource-using technologies are easier to substitute than others, and why lobbying for increased entitlement for scarce resources is a popular choice if the technologists can influence the government. In brief, the alternatives range from suffering the effects of scarcity to either developing new technologies, if they are perceived to be feasible to develop, or to lobbying for increased resource access. Furthermore, the essay warns that increased resource efficiency — a typical scarcity response — may in fact increase the total vulnerability of the technological system, as efficiency is almost always purchased with increased complexity and interdependencies that make total system change much more difficult.

This contribution builds links between (economic) scarcity and innovation literatures and provides a micro-level view into what the people who actually decide whether or not to initiate a research project to find alternative resources may think. It answers in part the call put forward in previous scarcity studies (e.g. Bretschger, 2005) for more detailed view into scarcity-induced innovation, and provides pointers for possible future research.

9.3 Managerial implications

The implications of this study are the same for both managers and non-managers.

9.4 Directions for future research

The topic of scarcities and constraints is a massive one, and detailed research into the topic is only beginning to emerge from the shadow of simple economic or systems theory frameworks. It seems likely that the future will have increasing demand for ideas and thinking that help the humanity to live within our means on a planet that is likely going to be home to ten billion people at least, and therefore further research, thinking, and discussion around the themes of "scarcity, abundance and sufficiency" (to quote Daoud, 2011) should be welcomed.

Furthermore, in the realm of historical research, the case studies covered in this thesis ought to provide pointers for historical researchers.

9.4.1 Organizational and economic research directions

For organizational and economic research, this thesis ought to demonstrate the value of historical method and deep longitudinal case studies when attempting to understand important phenomena. As the Essay I in particular notes, shallow histories that are typically used in case studies can be misleading, and researchers should think carefully whether the facts would permit even entirely different interpretations.

The case studies offered here might also offer jump-off points for further research, either as a continuation of these cases (the jet engine case in particular), or as components of a greater research program. Case studies of scarcity-induced innovation are rare, and given the importance of the topic, more studies should be welcome. One very potential topic would be the effects of the emission cheating scandal on car industries, mentioned several times in the text but not explored further. At the time of the writing, it seems that the scandal may prove to be one of the turning points that accelerate the phase-out of diesel vehicles entirely, in favor of mostly electric vehicles.

Organizational and economic research might also benefit from the distinctions between different scarcities expounded here. In particular, more research into quasi-scarcities would be most welcome. The caution advised in Essay IV about most scarcity research being based on case studies of relative scarcities should also inform future research. More studies into how scarcities, particularly material and energy scarcities, affect organizational decision-making should be interesting, at least from the theoretical point of view.

In general, research should probably not only move on from the fruitless fight between the resource optimist and resource pessimist extremes, but also reduce the emphasis placed in ecological economics research in particular on finding the "just right" regulatory and investment structures that would stimulate "green" innovation and economic growth while reducing environmental impacts and mitigating scarcities. Context matters, and it seems unlikely that the right prescriptions can be identified through research — although overviews (e.g. Kemp and Pontoglio, 2011) can provide useful guidelines. Furthermore, even if the correct prescription could be identified, enacting it politically and in a timely manner (as timing is an important determinant as well) is a different matter. The research might therefore serve the societies better if it put more efforts into examining how people actually cope with scarcities, and spreading such information more efficiently. The emerging resilience research is a welcome step to this direction.

On a more general level, this study provides some examples of how a theory of technology can be used to provide more detail in debates about technologies. By giving the technologies an interior and more detail, theories like recombinatory theory of innovation help us to understand that decisions about technologies are indeed sometimes dependent on the features of the technology itself. This is a more nuanced view than simple technological determinism, which has been roundly ridiculed in the science and technology studies during the last decades, but seems to explain many historical decisions better than theories that focus solely on social or political factors.

Finally, for innovation, organizational, and to a lesser extent science and technology studies, this thesis might work as an example of the importance and value of historical approaches, longitudinal research and considerations of deep prehistory of innovations. As noted by Edgerton (2006; 2010), histories of technology have too often been "stories for boys of all ages". Often too simplistic and too focused on singular inventions and singular inventors, these old stories about technology nevertheless remain influential in innovation research and scholarship, despite increasingly strident criticism from science and technology studies, history, and sociology.

9.4.2 Historical research directions

As this study is not strictly speaking a work of history, specifying future research directions for that field is somewhat difficult. However, the historical case study of Outokumpu could well be understood as a continuation of recent interest in the post-war Finnish history, and particularly its industrial history. The reinterpretation of Outokumpu's story practically asks whether other stories that have been adopted as part of standard narrative might be reinterpreted as well.

The study of the post-war energy shortage would also benefit from more detailed examinations. An interesting comparison for Outokumpu might be formed by the history of Vuoksenniska steel works: despite facing electricity price rises as well, there are no indications that this electric smelter developed novel technologies as a result. While this lack of results provisionally supports the theory presented in this thesis, that scarcities result to novel technologies only when the technology is almost ready for adoption, a more careful examination of Vuoksenniska's archives (currently at ELKA) might either support or disprove this notion.

What this research ignored almost entirely, except what information could be gleaned from public sources, was the Inco flash furnace story. This was caused primarily by the fact that remaining Inco archives, now apparently owned by a successor company Vale Limited, are currently closed to researchers. If the archives open, the history of Inco metallurgical research would be an interesting contribution to the history of metallurgical technology. Another possibly worthwhile topic would be the examination of Krupp-Grusonwerk's 1930s proposal for a furnace that Eero Mäkinen mentioned resembled the flash furnace idea.

On a methodical note, my study suggest that technology scholars and historians ought to be skeptical about claims made by technologists: as the Outokumpu case shows, what the technologists communicate to the outsiders may be quite different to what they themselves believe. Since minor differences in assumptions may mean major differences in the prescriptions, researchers would do well to be more careful in finding out just exactly what a technologist had in mind when announcing that something is or is not possible.

Chapter 10

Appendix

The metallurgy textbooks examined

With the exception of those marked with an asterisk (*), the following titles are available from HathiTrust Digital Library (www.hathitrust.org), to whom I extend my deepest gratitude.

On the Application of Electro-Metallurgy to the Arts. Elkington et al. 1844.

A brief account of the present organization of copper companies, now in operation on and about Lake Superior, for the digging and smelting of copper and other ores. Unknown, 1845.

A True Description of the Lake Superior Country; its Rivers, Coasts, Bays, Harbours, Islands and Commerce. St. John, John R., 1846.

Encyclopædia Metropolitana: Electro-Metallurgy (2nd ed.). Coleridge, Samuel Taylor. 1852.

A Manual of Metallurgy, or A Practical Treatise on the Chemistry of the Metals. Phillips, John Arthur. 1854.

The Chemistry and Metallurgy of Copper. Piggot, A. Snowden. 1858.

A Rudimentary Treatise on the Metallurgy of Copper. Lamborn, Robert H. 1860.

A Manual of Electro-Metallurgy: Including the Application of the

Art to Manufacturing Processes. Napier, James. 1860.

Metallurgy. The Art of Extracting Metals from their Ores, and Adapting them to Various Purposes of Manufacture. Percy, John. 1861.

A Treatise on Metallurgy; comprising Mining, and General and Particular Metallurgical Operations. Overman, Frederick. 1865.

A Manual of Electro-Metallurgy: Including the Application of the Art to Manufacturing Processes. Napier, James. 1867.

A Practical Treatise on Metallurgy, adapted from the last German edition of Professor Kerl's Metallurgy. Vol. II. Copper, Iron. Crookes, William and Röhrig, Ernst. 1869.

A Manual of Metallurgy. Greenwood, William Henry. 1874.

A Manual of Metallurgy. Greenwood, William Henry. 1875.

A Manual of Electro-Metallurgy: Including the Application of the Art to Manufacturing Processes. (5th Ed.). Napier, James. 1876.

Copper Smelting: Its History and Processes. Vivian, Henry Hussey. 1881.

Modern American Methods of Copper Smelting (1st Ed.). Peters, Edward Dyer Jr. 1887.

Electrometallurgy Practically Treated. Watt, Alexander. 1887.

Handy List of Books on Mines and Mining. Haferkorn, H.E.. 1891.

Modern American Methods of Copper Smelting (2nd Ed.). Peters, Edward Dyer Jr. 1891.

Modern American Methods of Copper Smelting (5th Ed.). Peters, Edward Dyer Jr. 1892.

Anaconda Copper Mining Co Foundry Department Catalogue no. 1.. Unknown, 1897.

Modern Copper Smelting (10th Ed.). Peters, Edward Dyer Jr. 1899.

Principles of Metallurgy. Hiorns, Arthur H. 1901.

Modern Copper Smelting (11th Ed.). Peters, Edward Dyer Jr. 1901.

Catalogue No.3 6th Ed. Roasting, Smelting, Refining. Allis-Chalmers Company. 1902.

Hyposulphite lixiviation; The Chlorination process; Copper smelting and refining; Lead smelting and refining; Zinc smelting and refining; Electrometallurgy. International Textbook Co. 1902.

Metallurgy: An Elementary Text-Book. Rhead, E.L. 1902.

Official Catalogue of Exhibitors: Universal Exposition. St. Louis, U.S.A. Department L: Mines and Metallurgy. Holmes, J. A. 1904.

Principles of Copper Smelting. Peters, Edward Dyer Jr. 1907.

Modern Copper Smelting (15th Ed.). Peters, Edward Dyer Jr. 1907.

International Mining Manual. Fifteenth Annual. Anonymous. 1907.

The Principles of Copper Smelting. Peters, Edward Dyer Jr. 1907.

Notes on Lead and Copper Smelting and Copper Converting. Hixon, Hiram W. 1908.

The Metallurgy of the Common Metals, Gold Silver, Iron, Copper, Lead, and Zinc (2nd Ed.). Austin, Leonard S. 1909.

Metallurgy: A Brief Outline of the Modern Processes for Extracting the More Important Metals. Borchers, W. 1911.

International Library of Technology: Blast Roasting. Anonymous. 1911.

The cyanide process, copper smelting and refining, zinc smelting and refining. International Correspondence Schools. 1913.

The Smelting of Copper Ores in the Electric Furnace. Lyon, Dorsey A. 1913.

Metallurgy of Copper. Hofman, H. O. 1914.

Recent Copper Smelting. Read, Thomas T. (ed.). 1914.

An Introduction to the Study of Physical Metallurgy. Rosenhain, Walter. 1914.

Practical Metallurgy and Assaying. Hiorns, Arthur H. 1914.

List of References on Concentrating Ores by Flotation. Cunningham, Jesse. 1916.

The Metallurgy of the Common Metals. Gold, Silver, Iron (and Steel), Copper, Lead and Zinc (5th ed.). Austin, Leonard S. 1921.

Metallurgy. A Condensed Treatise for the use of College Students and Any Desiring a General Knowledge of the Subject. Wysor, Henry. 1921.

Metallurgy of Copper (2nd Ed.). Hofman, H. O. 1924.

The Principles of Metallurgy. Bray, John L. 1929.

Vuoriteollisuus ja metallien valmistus. Mäkinen, E. 1933.*

Progress Reports – Metallurgical Division: 3. Studies in the Metallurgy of Copper. Dean, R.S. et al. 1934.

Progress Reports – Metallurgical Division. 18. Studies in the Metallurgy of Copper. Experiments in the flash-roasting of copper concentrates. Wartman, F. S. et al. 1937.

Metallurgy of Non-Ferrous Metals. International Textbook Co. 1940.

Metallurgy. Johnson et al. 1942.

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Non-Ferrous Production Metallurgy. Bray, John L. 1947.

Nonferrous Physical Metallurgy. Raudebaugh, Robert J. 1952.

Autogenous smelting of copper sulfide concentrates. Worthington, Robert B. 1973.

Metallurgy of Copper. Biswas, A. K. and Davenport, W.G. 1976.*

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Is necessity really the mother of innovation, and if so, why certain extremely urgent problems such as climate change or cheap energy storage remain unsolved? Why even extraordinary incentives often fail to generate technological change that would solve the problems the world is facing?

This thesis examines the relationship between resource scarcities and technological change, and asks when and under what conditions we can trust technologists to deliver technological solutions to problems of material or energy scarcity. It provides a theoretical overview of the scarcity and constraints literature, connects it to innovation management literature, and then illustrates the relationship between scarcities, constraints and technological change via historical case study focusing on the development of radically novel copper smelting technology by a Finnish mining company Outokumpu in the immediate aftermath of the Second World War.

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