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Innovation effects: Ersatz, or lasting improvements?

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Abstract

This paper examines the innovation effects of hypothesized extremely stringent environmental policy instruments through two historical case studies of innovations developed under severe resource constraints: the jet engine turbine cooling and flash smelting of copper. The goal of the paper is to shed light into possible dynamics of extremely strict regulation, which has been suggested to more readily result to beneficial, net-positive innovation effects. However, the findings of the case studies suggest that even very strict constraints seem to have had little effect on technological change, and the ?poisedness? for change of the technological system seems to be more important: if the system is not poised for change, even strict constraints have little effect. This suggests an alternative interpretation to several studies which have found the innovation effects to be dependent on the proper timing of the environmental policies. Furthermore, innovations developed as a result of strict constraints often take the form of ?ersatz? substitutions, which are used only because of the constraint. Conflating these with genuine technological advance seems to introduce a possible source of bias into studies of innovation effects that use proxies like inventive activity (patents) or innovation input measures (R&D) as proxies for innovation.

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Introduction

About 20 years ago, the noted economist Michael Porter challenged the conventional wisdom in a series of papers (Ambec, Cohen, Elgie, & Lanoie, 2011; Porter & van der Linde, 1995). He and his co-author Claas van der Linde claimed that stringent but "properly designed" environmental regulation would not only benefit the public through the mitigation of harmful externalities such as pollution, but also be advantageous to private firms. The private firms would benefit, the argument goes, from dynamic "innovation offsets" such as new and improved products and processes that the firms would not have had the incentive to develop without the prodding from the regulator. In particular, Porter argues that as waste and pollution are effectively wasted resources, environmental improvement and competitiveness come together at the level of resource productivity (Porter & Van der Linde, 1995). In the best case, these innovations might even more than offset the costs and effectively boost the competitiveness of regulated firms through improved efficiency or a first-mover advantage in markets that later embrace similar regulation. For obvious reasons, the argument has been highly appealing to policymakers as a painless remedy to environmental ills.

Unsurprisingly, this so-called "Porter hypothesis" and more general arguments of stringent (environmental) regulation either reducing intra-firm inefficiencies and organizational failures or providing positive externalities such as additional R&D (Mohr, 2002) have come under considerable criticism, particularly from neoclassical economists and innovation studies (e.g. (Roediger-Schluga, 2003, 2004). That environmental regulation may spur innovation is not and has not, by itself, been in doubt (Jaffe & Palmer, 1997), but the hypothesis in its stronger form is incompatible with the assumption of profit-maximizing firms, and rests on the idea that firms ignore — not only occasionally but almost systematically — what would be profitable opportunities. As far as theory goes, economists have derived possible, albeit rare, conditions under which regulation can induce innovations that fully offset compliance costs. For example, (Mohr, 2002) argues that firms may be wishing to move to a better technology, but want someone else to bear the short-term costs of adopting what may be an untested technology. In a similar vein, (Ambec & Barla, 2002) derive a theoretical foundation to the hypothesis, assuming that regulation creates external pressure that overcomes organizational inertia. However, more productive yet less polluting technology 1) must be available, 2) must remain unused, and 3) the regulation must favor the cleaner and more efficient technology for the conditions to apply.

Empirical efforts to test the innovation effects have largely focused on the impact of environmental regulation on competitiveness or innovation (for reviews, see e.g. Ambec et al., 2011; Kemp & Pontoglio, 2011; Lankoski, 2010). The results so far are mixed, with the majority of econometric studies investigating the links between the rigor of environmental regulation and shifts in trade patterns of pollution-intensive goods or the locations of capital investments producing few statistically significant results. Similarly, studies on the linkage between environmental policy measures and innovation (as measured in e.g. patents) have produced mixed results, with some studies showing a link where others failing to uncover a clear correlation (Kemp & Pontoglio, 2011). Moreover, what regulation tends to drive seems to be diffusion of pre-existing innovations, rather than innovation *de novo*. Among others, (Roediger-Schluga, 2004) argues that since radical technological advance is unpredictable, environmental regulation induces, at the very most, incremental improvements of existing designs. As the political costs of disrupting existing industry structures are high, regulation objectives are frequently adjusted or the compliance costs reduced through subsidies, further limiting the inducement effect (Roediger-Schluga, 2004). On the other hand, environmental regulation has little negative economic impact. Subsequently, several authors have argued that environmental regulations have so far been insufficiently stringent to induce innovation (Lanoie, Laurent-Lucchetti, Johnstone, & Ambec, 2011).

A major drawback in the aforementioned studies is their relatively high level of aggregation. Econometric studies use mostly country-level or highly aggregated industry-level data that may introduce a systematic bias, and obtaining accurate measures of the full costs of environmental regulation is difficult (see e.g. (Roediger-Schluga, 2003)). Furthermore, developing suitable measures for the stringency of environmental policy is similarly taxing. Innovation studies using aggregate patent data (e.g. (Popp, Hafner, & Johnstone, 2011; Popp, 2006)) and surveys (e.g. (Frondel, Horbach, & Rennings, 2007)) offer a somewhat more nuanced view, but the dichotomy of mixed results remains troublesome. In any case, econometric studies (and, to a somewhat lesser extent, survey-based studies) suffer from the difficulties in the measurement of innovation. As Kemp and Pontoglio (2011) note in their recent review, only one econometric study (Newell, Jaffe, & Stavins, 1999) has measured innovation output (new product models) instead of inventive activity (patents) or innovation input measures (R&D). The problem is that the majority of environmental innovations are not patented and are thus missed, and data on environmental R&D is often not available (Kemp & Pontoglio, 2011; Mazzanti & Zoboli, 2006). Furthermore, the measures commonly used — inputs and inventive activity — may not be good proxies for the actual significance of innovations developed as a result of regulation, and the studies often fail to distinguish between new to the world and new to the adopter innovations (Kemp & Pontoglio, 2011), i.e., between innovation and the adoption of innovations. Although survey studies have been able to gather richer data, they are mostly focused on the adoption of pre-existing technologies (Kemp & Pontoglio, 2011). Case studies detailing radical technological change as a result of regulatory changes remain rare.

Nevertheless, case studies on individual technologies allow for the reconstruction of causal chains and the incorporation of a wide range of factors in the analysis. Cases and mixed-method studies such as (Mickwitz, Hyvättinen, & Kivimaa, 2008), (Yarime, 2007) and (Christiansen, 2001) suggest that innovation effects depend heavily on the characteristics and timing of the regulatory measure, and on the nature of the innovation (process or product, for example). In other words, innovation effects seem to be heavily context-dependent. This substantial context-dependency raises a question about the efficacy of environmental policies in promoting innovations. In particular, the dependence of innovation effects on accurate timing of the regulation (as noted by e.g. (Kemp & Pontoglio, 2011; Kivimaa, 2008; Sartorius & Zundel, 2005)) seems to suggest a possibility of alternative interpretations.

This paper explores an alternate interpretation of innovation effects by looking into the Porter Hypothesis in a slightly different light. Instead of looking for regression-amenable proxies for competitiveness, innovation and strictness of environmental policies, I will begin by broadening the hypothesis to a more general case of innovation under constraints, and then look for evidence for and against the hypothesis from the microhistories of two case studies of innovation in technological systems. Instead of looking into specific cases of eco-innovations developed as a result of environmental regulation, I expand the research question to i) look for long-term trends in technological systems (T.P. Hughes, 1983; Thomas P. Hughes, 1987) where the innovations are embedded in and ii) include innovations that were developed as a result of strict scarcity of a critical resource. Namely, I look into microhistories of jet engine turbine and copper smelting furnace design. In both technologies, lack of critical resources (strategic metals in the jet turbine case, electricity or fossil fuels in the copper smelting furnace case) caused certain firms to develop novel technologies that overcame the challenge. In one case, the results were broadly adopted around the world; in the other, the constraint was overcome but the resulting technology turned out to be a dead end with little further development potential, and was abandoned as soon as the constraints were lifted.

This approach brings several advantages. Beyond the evident one of enlarging the selection of case studies, perhaps the most important advantage of this approach is that it allows a closer look at the possible consequences of extremely stringent environmental regulation. A running theme in research on innovation effects of environmental policy instruments is the stringency of environmental regulation, with the assumption that more stringent regulations would lead to more innovation. Several authors have suggested the lack of stringency of regulation as a possible reason why innovation effects have so far largely eluded researchers (e.g. (Kemp & Pontoglio, 2011; Roediger-Schluga, 2004)). Therefore, it would seem reasonable to believe that studying innovations that have been enabled by strict constraints — an absolute or near-absolute lack of a certain resource that forces the system builders to make changes in the system — might tell us something useful about the dynamics of extremely stringent environmental policies. The role of constraints in general in problem-solving is a topic that has seen considerable discussion in cognitive science, creativity and innovation literature (see e.g. (Joyce, 2009; Moreau & Dahl, 2005; Ward, 1994) as an example of the former, and (Gibbert, Hoegl, & Välikangas, 2007; Gibbert & Scranton, 2009; Gibbert & Välikangas, 2004) as an example of the latter research streams).

Of course, the approach also has its drawbacks. Readers will be familiar with the dangers of generalizing from case studies, and I do not claim that the cases presented here are any different. A skeptical reader might also question whether the dynamics of scarcity-induced innovations differ from the dynamics of tightening environmental regulation. This is a valid point, but the similarities and dissimilarities remain a matter of subjective judgment. Furthermore, consider what the stronger form of the innovation effects hypothesis actually proposes: that pressing needs somehow (as the actual cognitive mechanism remains somewhat unclear) stimulate the innovators (be they individuals or organizations) to come up with solutions that they wouldn't have otherwise thought of. According to literature on the role of constraints in problem solving (see e.g. (Joyce, 2009; Moreau & Dahl, 2005; Ward, 1994)), the dynamics do not seem to depend on the source of constraint. Of course, the details — where the devil is all too frequently to be found — may differ, and I leave it to the reader to judge whether the cases presented here might have broader validity.

In particular, I wish to advance two concepts that bear relevance to the discussion of technological change: the poisedness of the technological system, and the concept of "ersatz" technologies. The poisedness, or "structural vulnerability to innovation and invention" to use the terms of Padgett and Powell (2012, p. 26), refers to the fact that certain system configurations in a certain moment of time are more poised for a change in response to a perturbation than others (see (Padgett & Powell, 2012)). In technological systems, one way in which poisedness manifests itself is a condition of intellectual ferment, where relatively large numbers of rich descriptions, experiments and analyses arguing for the potential for alternative concepts and designs appear over relatively short period of time. The concept is related to stages of technology life cycle in technological change literature (see e.g. (Anderson & Tushman, 1990; Kaplan & Tripsas, 2008)). There a term "era of ferment" is sometimes used to describe the initial life cycle stage of variation, which is characterized by high turbulence and uncertainty in user preferences and characteristics of the technological system (e.g. (Kaplan & Tripsas, 2008)). However, I feel that the term "poised for change" or "poisedness" captures the state of the system more accurately, while highlighting the primary question under study: how do constraints work in promoting technological change?

The second concept advanced in this paper is that of "ersatz" technologies. The term comes from a German word for substitute or replacement, and gained international attention during World War I, as besieged German industry was forced to develop substitutes for many provisions. It generally connotes artificial and inferior substitutes and imitations, and as such, seems to be a good term for technologies that would probably not be used unless users are forced to do so by some constraint or another. In particular, I use the term to denote technologies and technological solutions that are adopted even if superior solutions are known to exist, simply because the designers have to comply with a specific constraint. The use of *ersatz* concept helps to differentiate between different types of innovations: particularly when discussing innovation offsets and innovations thought to be an answer to a constraint (whether a regulatory or material), it seems to be important to define whether the innovation represents genuine technological advance or is simply something that is used as a substitute for the "real thing." The lack of such quality differentiator in prior studies about innovation effects is somewhat puzzling: as it does not seem to be in doubt that regulation influences innovative activities (Jaffe & Palmer, 1997), analyses using the amount of inventive activity as a proxy for innovation effects without much concern about the quality of outcomes would seem to have a potentially significant source of bias.

Regulation and scarcities: different or similar?

An astute reader will no doubt point out that regulation that aims to reduce environmental impact and scarcities that have been caused by e.g. lack of access to energy or raw materials are different beasts altogether. For example, it could be argued that regulation aimed at pollution reductions mostly raises the cost of some input relative to others, while scarcities represent more or less absolute lack of some material. In a similar vein, one could argue that the time dynamics are different. Regulations typically include a prolonged negotiation process between different stakeholders, who thus become informed of proposed legislation, and almost always include lengthy phase-in periods, while scarcities caused by disruptions such as wars and other political crises are much more sudden and leave little time for preparations before the event. Finally, regulations are typically not dictated to firms but instead result from a political tug-of-war between competing interest groups, whereas scarcities could be seen to be exogenous and beyond the influence of industries. However, a closer examination reveals that scarcities and constraints have more similarities than differences, and suggest that regulations and material scarcities might be more fruitfully viewed as slightly different parts of the “constraint continuum.” On one end of the continuum are “lax” constraints, such as regulations like taxes that (slightly) affect the price of a certain input. On the other end are “stringent” constraints such as utter lack of the same input. Viewed in this way, typical real-world environmental regulation (e.g. emission limitations) is somewhere closer to the “lax” end of the spectrum, while scarcities may be found closer to the stringent end. However, as the cases will show, even wartime scarcities are seldom absolute or even beyond control of the involved firms: in both cases, the critical resources (strategic metals, electricity, fossil fuels) were available, albeit at a greatly reduced extent. One could plausibly argue that the scarcities were at least partly socially constructed and the firms had the alternative of persuading the authorities to relax the constraint by releasing sufficient quantities of critical materials, had they not been able to come up with their resource-saving innovations. The dynamic seems to be similar to e.g. a regulatory case studied by Roediger-Schluga (2004), who detailed several regulatory renegotiations as firms persuaded the authorities to relax initially strict environmental regulations because — contrary to optimistic expectations — technical solutions were not forthcoming. Likewise, the suddenness of scarcities is often more apparent than real. For example, the jet engine case study will show that wartime constraints of raw materials were in fact anticipated by jet engine designers and solutions were developed far in advance of the actual constraint. In a similar vein, copper smelting technology had been developing for decades into a direction of reduced energy use, and copper smelter designers were able to draw from this body of experience when the push came to shove and radically more efficient furnaces were needed. In short, I argue here that scarcities and regulatory constraints share enough common mechanisms for the case studies of scarcity-induced innovation to be fruitfully used to study the effects of stricter environmental regulation on innovation.

Cases and a note about the methodology

The two case studies presented in this paper, the development of jet engine turbine technology during the Second World War and the development of novel copper smelting methods immediately after the war, are used as examples of innovative activities that resulted from strict material constraints of the time. The selection of case studies was based on literature search about constraint-induced innovations. The turbine developments have been seen as an example of such by e.g. (Gibbert & Scranton, 2009; Giffard, 2011), while (Särkikoski, 1999) and (Habashi, 1993, 1998) consider the development of copper flash smelting as another prominent example. Furthermore, both of these cases of technological change had significant historical impacts: in the first case, turbine development enabled the Germans to build serviceable jet engines despite severe material shortages, and in the second case, the resulting furnace design today accounts for up to 50% of world's primary copper manufacturing capacity (Moskalyk & Alfantazi, 2003) and is acknowledged to be one of the major metallurgical breakthroughs of the 20th century (Kojo & Storch, 2006).

The selection of cases was also influenced by the wealth of material available, as both cases could be readily studied using both contemporary accounts in e.g. trade press and detailed secondary sources. Besides sources mentioned in the text, contemporary archives of *Flight* magazine and *Journal of Metals* (the leading trade publications, respectively) provided complementary evidence, as did other archival sources such as patent databases. Semi-structured interviews and correspondence with subject matter experts rounded up the cases and helped to clarify otherwise problematic issues.

In the following two case studies, the words *concept* and *design* have special meanings. Concept refers to a general way of how a certain problem may be solved, for example, that a problem with excessive heat may be solved by cooling or using more heat-resistant materials. Design refers to the particular way the concept is realized in practice, for example, whether cooling is achieved via drilling cooling channels to the heat-stressed component, or making the component hollow from the start. Dissimilar artifacts and technological systems may incorporate similar concepts but different designs, or different concepts and different designs, or (very rarely) different concepts but different designs.

Jet engine turbine cooling

The first case study is concerned with the development of a crucial component within jet engines, their turbine. To understand the importance of the turbine, a brief primer of jet engines is necessary. Jet engines are a form of gas turbine engines used to power aircraft. First developed just before the Second World War, the gas turbine engine not only enables cheap mass travel but also powers increasing numbers of naval and land vehicles and stationary power plants. A schematic of a turbojet engine is shown in Fig. 1. A gas turbine operates by first compressing air in a compressor. The compressed air is mixed with fuel (either gaseous or liquid) and ignited in a combustion chamber. The heat generated by the fuel expands the gaseous mixture, and this expansion is directed through turbine at the rear of the engine. The turbine blades convert a part of the energy of the hot gas into rotary motion, which in turn powers the compressor via a shaft running through the engine. In jet engines, the rest of the hot gas is exhausted from the rear, providing forward thrust for the aircraft.

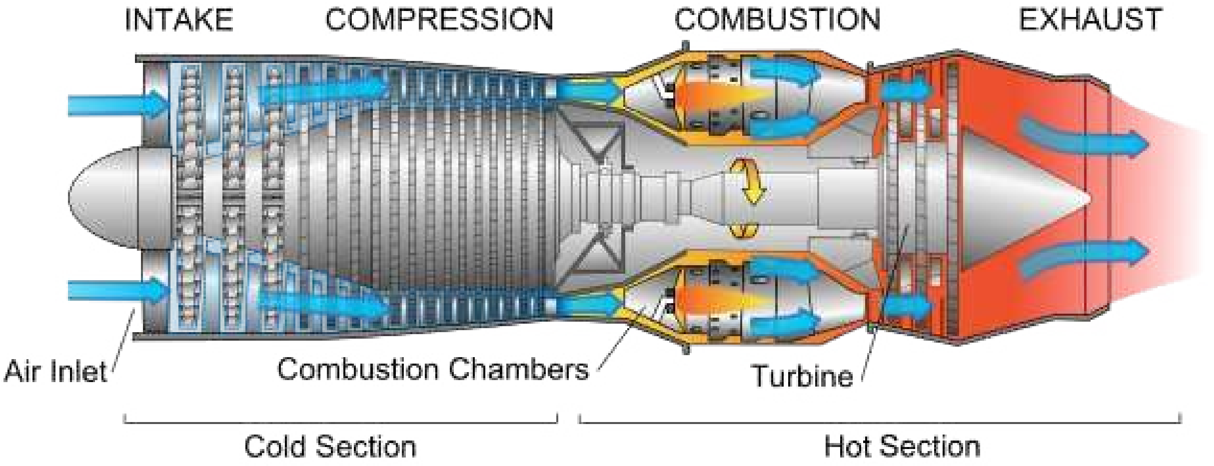

Figure 1: Schematic of axial flow turbojet engine. (c) Jeff Stahl 2007.

As far as the aircraft jet engines are concerned, the pioneering work in the field is usually credited to Frank Whittle, in the UK, and to Hans von Ohain, in Germany, who patented their independent designs in 1930 and 1935 respectively. For the purposes of this case study, it is not necessary to go into details about the considerable difficulties faced by these early developers (the reader is directed to the overviews in (Constant, 1980), (Gunston, 2006) or (Giffard, 2011) instead). The history shows that ultimately, the Germans were the first to achieve jet-powered flight, while the British were the first to field operational jet aircraft (the Gloster Meteor I, which entered limited squadron service in July 1944, although German Me-262 was the first jet to be used in combat). Instead, I will focus on the development of a key component within the engine: the turbine blades.

In many ways, the turbine blades, located directly behind the combustion chamber and receiving full-on the blast of superheated air, determine the maximum safe operating temperature and hence set the engine's performance limits: the hotter an engine can be made to (safely) run, the more power it produces with the same amount of fuel. Thus, jet engine designers have for long had the incentive to use as heat resistant materials as possible in order to increase the operating temperature. Many other parts of the engine can be protected from the heat using relatively simple refractory materials and cooling solutions, but the turbine blades present a major problem. The blades must withstand not only high temperatures but also severe stresses, particularly centrifugal forces, imparted in a turbine rotating up to 20,000 revolutions per minute. In this environment, most materials deform slowly in a phenomenon known as creep. As the tolerances within the engine need to be very tight, even small deformations in an operating engine's turbine can cause a spectacular explosion. In short, the construction of creep-resistant turbine blades posed perhaps the most forbidding problem facing early jet engine developers (Constant, 1980, p. 258). As the engine designers sought higher performance and efficiency (a desire that continues today, in the form of lower fuel consumption), higher permissible turbine blade temperatures were desired. The most obvious way of achieving this was to use increasingly heat-resistant nickel and chrome alloys, and all the early prototype engines used special alloys with high nickel and chromium content. These blades were usually either forged or machined to a desired aerodynamic shape from a solid "blank" of material.

However, as e.g. (Gibbert & Scranton, 2009) have noted, the German engineers during the Second World War faced a particular problem. Unlike the Allies, Germany was cut off from the most deposits of these critical metals, and their use had to be judiciously rationed. The German jet engine designers participated in a concerted effort to reduce the use of these strategic materials in their jet engines, and succeeded in reducing their use to about half (Kay, 2002). The key concept that allowed the use of less heat resistant alloys that were more economical with scarce materials, was to cool the blades actively to keep their temperatures within acceptable range. In the German design, cooling was achieved by manufacturing the blades by drawing and welding from sheet metal into hollow shapes. This, in turn, allowed air drawn from the compressor and ducted to the turbine disk to cool the turbine blades from inside. An added — and, according to Giffard (2011) a significant — benefit of sheet metal turbine blades was the reduction in man-hours (especially of skilled labor) required to manufacture the engines; by the end of the war, the main production engine, Jumo 004-B-1, required only 700 man-hours to build, less than one fourth of the time spent on German piston engines and a fraction of time required by British jet engine designs (Giffard, 2011:105).

Because the British wartime jet engines did not utilize the same concept, Gibbert and Scranton (2009) have suggested that the hollow blade is an example of an important innovation that was developed because of a resource constraint. While this is one possible interpretation, a broader view of the technological system and its development trajectory suggests that the true value of the innovation is less clear. Blade cooling was explored even before the war and German experiments with internally cooled turbine blades were even reported in the prestigious Flight magazine in 1938 (Anonymous, 1938). As e.g. Giffard's extensive study (Giffard, 2011) shows, German engine designers were well aware that in the event of war, Germany would probably be isolated from most of the sources of nickel and chromium, and therefore designs with less reliance on them were highly desirable. Nevertheless, both nickel and chromium continued to be available in Germany right to the end of the war. Furthermore, jet engines used only very limited amounts compared to e.g. armaments industry: as the Table 1 shows, the total strategic material consumption of the most-used German jet engine was minuscule compared to other demands.

Table 1: Critical metals used in German Jumo 004 jet engines, with monthly consumption as reference. From Kay (2002:16,78).

.	**Per engine**		**Approximate totals (6000 engines produced)**	**Monthly consumption in November 1943**
	004-B-1	**004-B-4**		
Chromium	6.35 kg	4.7 kg	33 tons	3751 tons
Nickel	9.85 kg	3.5 kg	40 tons	750 tons

Both internal and external cooling of turbine blades[1] were also tested in British prototype engines (built by Rolls-Royce) as early as in 1942 (Eyre, 2005), but as Gibbert and Scranton (2009) acknowledge, the availability of creep-resistant steel and nickel alloys was the direct reason why the British designers did not have to devote resources into developing hollow blades for production engines. This was a major benefit, as hollow blades represented a significant technological challenge in itself: as Kay (2002) discusses in his comprehensive history of German WWII jet engine development, the production of hollow blades of adequate quality was very difficult, and ironing out the problems took considerable time. Even so, the limitations of the manufacturing method forced the designers to make compromises in the aerodynamic shaping of the turbine blades, which harmed the engine performance (Kay, 2007). The air cooling system also imposed a performance cost of some 2% of overall engine power, although the cooling improved the lifetime of the engines and allowed the temperature and hence the power rating to be raised, usually more than offsetting the loss.

Revealingly, the hollow blade concept, as originally designed, was not used in any post-war jet engines. For the first few years of the post-war period, jet engine developers could use new nickel-based high-temperature alloys without cooling, as other factors such as compressor inefficiencies formed the “reverse salients” (T.P. Hughes, 1983) limiting the engine performance. However, the limitations of the alloys were anticipated, and as early as in 1952, Rolls-Royce in UK (a post-war pioneer in jet engine development) returned to air cooled blade concept. The initial test engine used welded sheet metal blades similar to the German hollow blade design, but by 1954, a subtly but importantly different design — with far greater development potential — had emerged (Gunston, 2006, p. 95).

The original German hollow blade design had used blades that were either drawn or wrapped and welded from sheet steel. This resulted in thin-walled, light blades that were very economical in their use of scarce metals, but the manufacturing method is ill-suited for more advanced heat-resistant alloys (which are often difficult or impossible to work in sheet form) and impose severe restrictions on the aerodynamic shaping, as previously mentioned. Probably because of these issues, the ultimate Rolls-Royce design started from high-alloy blades, but added narrow cooling channels via complex process of drilling and forging. The result was a turbine blade that was far superior in heat resistance, strength, durability and aerodynamic shape. Although manufacturing methods have developed since, I’m not aware of a single instance

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[1] In external cooling, one end of the blade was exposed to a cool air flow.

where the original German design (i.e. turbine blades drawn or wrapped from sheet metal) or even variations that could reasonably have said to be inspired by it (e.g. thin-walled turbine blades or turbine blades with large cooling channels relative to size) have been realized in operational post-war jet engines.

Of course, it may be argued that the fundamental idea or impetus for later blade cooling systems came from the examination of captured German jet engines and documents, or from German aircraft engineers who found work outside Germany (Gibbert & Scranton, 2009). Although Rolls-Royce was certainly informed of the German jet engine design (captured engines were studied in detail and a detailed analysis (Foster, 1945) appeared even in open trade press less than three months after the end of the war), it does not follow that the concept would have been left unexplored even without any contact. From an engineering point of view, cooling is an obvious solution any time a component is subjected to too high temperatures. It is almost inconceivable to think that any proficient engineer would have failed to consider cooling the turbine blades, and once cooling is considered, internal cooling is probably the most straightforward approach, as evidenced by the British tests of actively cooled blades in 1942. In my personal judgment, the most likely reason why cooling was initially ignored but later adopted in British production engines was simply because it was initially not worth the effort and the tradeoffs, but soon became both necessary and obvious solution.

The most damning indictment of the sheet-metal blade design is that when the original German design team with perhaps the most experience in hollow blades was invited to France to continue the development of their engines, they almost immediately abandoned the hollow blades in favor of solid, high-temperature steel alloy blades similar to those used by the British during the war (Kay, 2002, 2007). Perhaps the more realistic view of the development of blade cooling is to view it as an example of convergent evolution: because the environment where the blades operate is similar, the designs look superficially homologous, but have very different pedigrees and internal structures.

The German design might be better understood as an example of *ersatz,* or low-quality substitute — the "mend and make do" of wartime propaganda posters. Without material scarcity, the jet engine technological system of the 1940s would not have been poised for a change: blade cooling was an innovation before its time. The contribution of the German design is largely limited to saving of critical raw materials it engendered, and while undoubtedly an ingenious technical achievement, its practical significance to technological history remains limited. As a British wartime evaluation of a captured German early-model Jumo 004 B-1 jet engine states,

> *"For general future design of gas turbine engines, there does not seem much to be learned from this engine. The enemy has always tended to sacrifice everything for production and has made strenuous efforts to overcome his shortages. In consequence, performance has suffered but it still shows that a useful jet engine can be built even when heat-resisting steels are in short supply."* (Power Jets Report No. R.1089, quoted in (Kay, 2002, p. 92))

In summary, the effect of extreme raw material scarcity seems to have been the acceleration of the adoption of the air cooling concept by nine years at most. However, the adoption was premature, the approach chosen did not have development potential, and the concept was abandoned for nearly a decade before rising performance demands forced engine designers to use the concept again — but from a different starting point, and with a considerably different design approach. Furthermore, the constraint-induced innovation did not result to any lasting changes, and from this viewpoint, its significance may be questioned. While stopgap or *ersatz* solutions are interesting examples of scarcity-induced innovations, they are not very relevant from the innovation offsets point of view: it would seem to be obvious that stringent constraints must have some effects on engineering design (otherwise they wouldn't be stringent), but the innovation offsets discussion seems to be mostly interested on whether the effects are net positive, i.e., whether they result to *improved* performance in the long run. In this case, the answer seems to be mostly negative.

Flash smelting of copper

The second case study is concerned with the development of novel copper smelting methods in the period immediately following the Second World War. In the late 1940s and early 1950s, two metal manufacturers — nickel giant INCO in Canada and a small state-owned copper mining company Outokumpu in Finland — developed radically new copper smelting furnaces that greatly improved the energy efficiency of copper smelting.

These so-called "flash furnaces" generated heat by burning dust-like sulfurous copper ore in preheated air (Outokumpu method) or oxygen-enriched air (INCO method). Compared to earlier furnace types, both of these furnaces saved considerable amounts of fuel, even when the electricity required for oxygen generators was accounted for. Another advantage of these furnace types was that the polluting flue gases could be more easily captured and treated. These advantages, linked to a successful technology sales strategy, resulted to Outokumpu furnace becoming the most important primary producer of copper today.

The development of Outokumpu furnace has been detailed in Särkikoski (1999), and its genesis is commonly attributed to electricity shortages plaguing post-war Finland (Habashi, 1993, 1998; Kojo & Storch, 2006; Särkikoski, 1999). Just before the war, Outokumpu had constructed what then was the world's largest electric smelter for copper, but the outcome of the war left fully half of the country's electricity generating capacity to the Soviet side of the border (Newton & Wilson, 1942; Särkikoski, 1999). Outokumpu's management considered several solutions to the pressing problem — exacerbated by the fact that copper was critically important both as a source of foreign revenue and as a part of war reparations — but ultimately decided that time was ripe for a resurrection of an idea over 80 years old (Sticht, 1898): burning of sulfur in sulfide ores. The key concept that allowed successful sulfur-fueled smelting (so-called autogenous smelting) was to reduce energy losses that occurred via furnace flue gases. The core solution developed by Outokumpu was to use heat exchanger to improve the energy balance of the process, so that much of the heat previously wasted with flue gases could be recycled in preheating incoming air. In this original form, the Outokumpu furnace could smelt copper even completely without extraneous fuels.

Despite post-war difficulties in obtaining even basic construction materials, a pilot plant was fired up for the first time in February 1947, less than two years after the project was started (Bryk, Ryselin, Honkasalo, & Malmström, 1958). Commercial operation followed on April 20th, 1949 (Kojo & Storch, 2006).

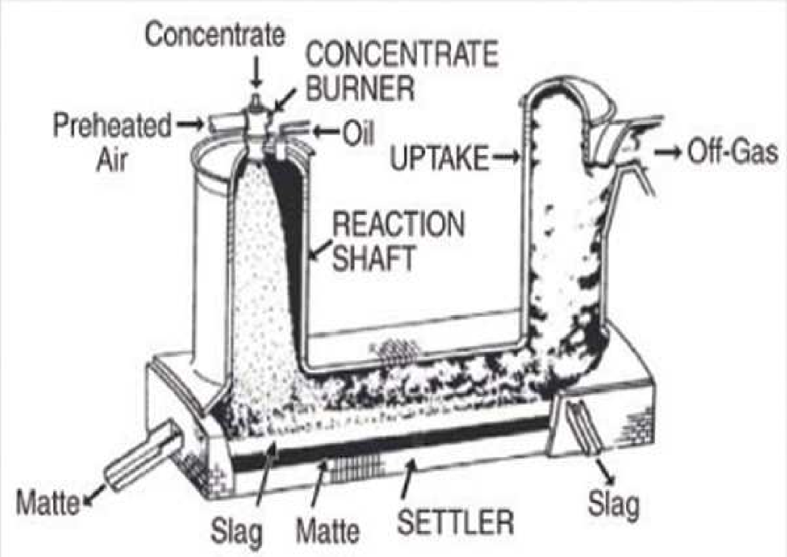

Figure 2: Outokumpu flash furnace (without heat exchanger).From (King, 2007).

Meanwhile, in Canada the nickel giant INCO had also been developing a novel method for smelting sulfide ores. It design was based on the same concept — that sulfur in powdered copper ore concentrate could be burned and the heat used to smelt the ore, if heat losses could be minimized — but the design was different. Before the war, one of INCO's researchers had conducted a detailed theoretical study of the problem of smelting copper concentrates without the use of extraneous fuels (Norman, 1936). The conclusion of this study was that the heat balance of the process was not sufficient, unless remedial measures were taken, as too much heat was absorbed by inert nitrogen introduced by the air blast and lost with the flue gases. If, however, the concentrate were burned in an atmosphere of 40-95% oxygen, then there would be less gas to absorb the heat evolved. A higher temperature could be attained, and sulfide ores would melt. Another advantage of using oxygen, one that was very important to INCO, was that oxygen-based process could be more easily adapted to nickel smelting as well (Brundenius, 2003).

Based on these results, INCO's engineers focused on using oxygen-enriched air in a traditional "reverberatory" furnace. The benefits of using oxygen were well known to metallurgists even in the 1800s (Davis, 1923), but for long, the problem had been the affordable tonnage production of the gas. This problem was largely solved by the 1930s by developments of air liquefaction process by Linde in Germany and Claude in France, however (Greenwood, 1919; Newton & Wilson, 1942), making the copper smelting technological system poised for a transition[2]. After the wartime focus on maximizing production using established techniques abated, INCO's engineers were able to continue their successful experiments (Queneau & Marcuson, 1996). Pilot plant was operating in January 1947 and, although delayed by problems with oxygen generators, commercial operation started on January 2, 1952 (Inco, 1955; Queneau & Marcuson, 1996).

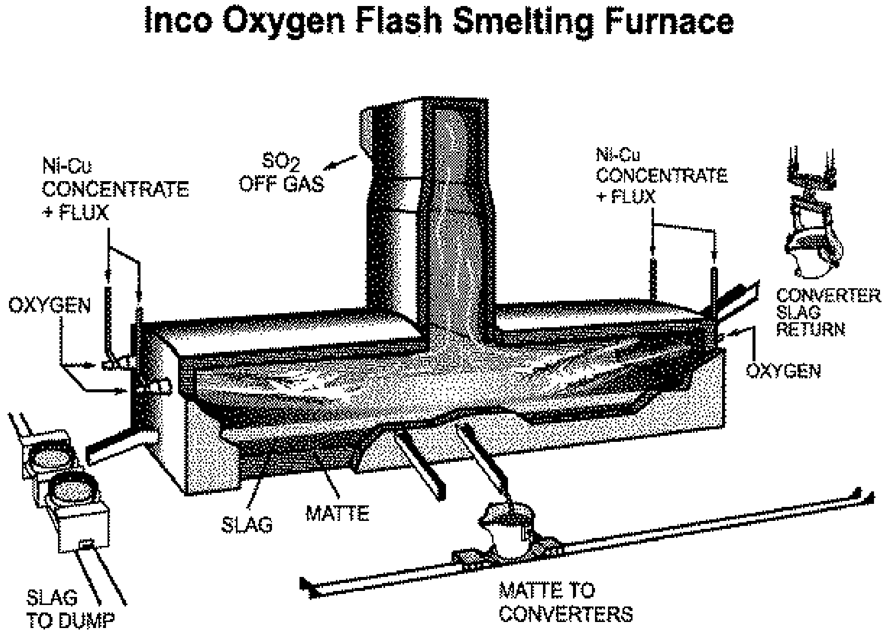
Inco Oxygen Flash Smelting Furnace

Figure 3: INCO flash furnace. From (Queneau & Marcuson, 1996).

At the first sight, the development of Outokumpu's flash furnace could be interpreted as an example of a positive innovation effects. First, it seems likely that Outokumpu would not have developed its furnace without the electricity constraint; as an example, Boliden copper smelter in neighboring Sweden was modernized at the same time but retained the use of tried and true electric furnaces (Herneryd, Sundström, & Norra, 1954). Second, the Outokumpu furnace became a clear commercial success, being licensed to 44 smelters around the world and spawning a mining technology company Outotec (Kojo & Storch, 2006), while INCO furnace has been used only in three smelters. Third, the method was a substantial improvement upon earlier practice, greatly reducing energy consumption (fig. 4) while enabling relatively easy emission controls. In fact, the latter feature was one of the strongest selling points for the flash furnace, once air pollution standards tightened worldwide starting from the 1960s (Särkikoski, 1999).

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[2] The revolutionary effects of readily available tonnage oxygen after the Second World War were felt in almost every subfield of metallurgy, with particularly significant impacts to steelmaking via basic oxygen steelmaking process introduced in the early 1950s

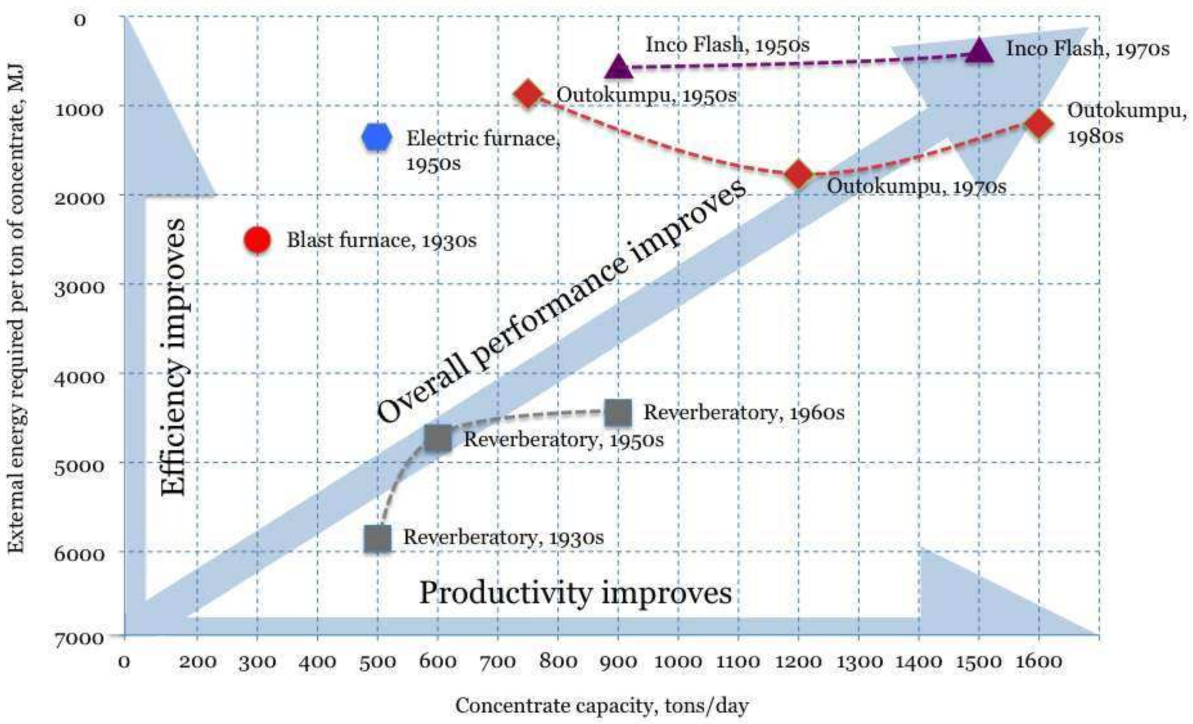

Figure 4: Development of copper smelting furnaces, 1930-1980. Data from (Biswas & Davenport, 1976; Davenport, King, Schlesinger, & Biswas, 2002) and U.S. Bureau of Mines Mineral yearbooks.

However, a closer look at the facts suggests that these conclusions may exaggerate the innovation effects. First of all, the idea of using sulfur in sulfide ores as a replacement fuel was anything but new. Sticht (1898) traces the first published proposal to 1866, with first full-scale furnaces being built in 1881. These furnaces were designed for relatively rich block ore with a specific chemical composition, and fell out of use once these ore bodies had been exhausted. However, proposals for adapting the method for powdered ore concentrate appeared even before methods for producing powdered concentrates were fully developed, with the first U.S. patent for smelting powdered sulfur-bearing ores “in a single apparatus… solely by heat generated by their own combustion” appearing in 1897[3] (Bridgman, 1897, p. 10). Between 1897 and 1939, furnaces that were very similar in principle if not in every detail had been designed and constructed by at least seven different institutions or individuals, a fact readily admitted by contemporary accounts by Outokumpu’s engineers (Bryk et al., 1958). Even the key component, the heat exchanger, had been anticipated before the war (Zeisberg, 1937). The differences to

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[3] The froth flotation process that produced powdered sulfide ore concentrate became widespread starting from 1912 (Callow, 1916; Mäkinen, 1933).

earlier designs were so small that Outokumpu had trouble patenting its furnace in the U.S. (Särkikoski, 1999). The speed at which the first pilot plant was constructed speaks volumes about the maturity of the technology and the poisedness of the system: even though no full-scale furnaces of that particular type had been constructed and operations were hampered by lack of even basic building materials, the engineers at Outokumpu were confident enough to essentially gamble the future of the company on the assumption that they could pull it off. In terms of Constant (1980), burning powdered ore concentrate was a new normal technology. Although Outokumpu was the first to take the financial risk of constructing the pilot plant, it seems that other companies would inevitably have done the same sooner or later.

Second problematic aspect of the narrative is the uncomfortable fact that the performance of Outokumpu's furnace was in fact clearly inferior to INCO's flash furnace, and remained so until the key feature of INCO's method — oxygen enrichment — was copied in the 1970s (Biswas & Davenport, 1976; Kojo & Storch, 2006) (see Fig. 4). Outokumpu's engineers were clearly aware of the desirability of oxygen injection, originally even considering the adoption of an oxygen-based process, but were prevented from doing so by lack of availability of suitable oxygen generators in Europe of 1945 (Särkikoski, 1999). Furthermore, oxygen generators required secure electricity supply (albeit at much lower levels compared to direct electric smelting), which was the cause of Outokumpu's problems in 1945 in the first place. Instead of oxygen generators, Outokumpu had to resort to complex and troublesome but relatively low-tech heat exchangers. These improved the heat balance that had bedeviled earlier attempts, but at a cost of continuous breakdowns and maintenance problems. It is telling that as soon as fossil fuel oils were again readily available in early 1950s, the heat exchanger was ditched in favor of simple oil-fired air preheaters (Särkikoski, 1999). These simplified operations and helped to achieve higher productivity with, for the time, acceptable losses in energy efficiency — but INCO's method achieved both high productivity and high energy efficiency.

Of course, one must also explain why Outokumpu and not INCO method became the industry standard. Contemporary accounts were puzzled by this mismatch: for example, a textbook of copper metallurgy stated as late as in 1976 that the success of Outokumpu's method was "somewhat surprising," because "it appears that the INCO process is the better from both a technical and economic point of view" (Biswas & Davenport, 1976, p. 170). Brundenius (2003, pp. 24-39) has convincingly argued that the reason for this mismatch can be found from the different strategies of the two companies. INCO's main business was the production of nickel, and the oxygen process was extremely lucrative for nickel smelting as well. Naturally, INCO did not want its competitors to have this advantage. Besides, technology sales were probably seen as a relatively unimportant to a major player like INCO: the first license of Outokumpu's furnace brought revenues of just $1.3 million in 2010 dollars (Särkikoski, 1999). This low price partly reflects the fact that what licensees bought was not so much technology — the basic idea was well known, and most competent metallurgists could have designed a similar furnace — but reliability, experience with the process, and a tested design with a network of known suppliers for parts and expertise (Särkikoski, 1999).

In short, Outokumpu's revolutionary and radical innovation was premeditated by nearly hundred years of metallurgical "normal technology" (Constant, 1980), and the key feature of its claim to radicalness was more or less an “ersatz” technology, inferior in quality and put into use at a time — and only for a time — when alternatives were simply not available. Furthermore, when flash smelting technology is viewed in its historical context, its adoption seems to be more of a case of diffusion of several related innovations (burning of powdered ore, the use of oxygen generators) in a system poised for the diffusion, rather than remarkable innovation *de novo*.

Conclusions

The cases present an interesting possibility for a hypothetical what-if argument that may shed light to the questions posed in the introduction: does stringent regulation promote radical innovation, and what might be the be alternative interpretations of the existing research on innovation effects of environmental regulation (in particular, about the timing of environmental regulation, e.g. (Kemp & Pontoglio, 2011; Kivimaa, 2008; Sartorius & Zundel, 2005))?

To answer this counterfactual, let us consider how the evidence might be interpreted if the scarcities had been the result of (environmental) regulation, for example, heavy taxes for heavy metals in the jet engine example, and for electricity in the copper smelting case. In these cases, the evidence would show the emergence of radically new technology after the “regulation.” This could be construed as evidence for positive innovation effects. Had the constraints remained in force, the technologies in question would probably also remained in use, and the statistics would show benefits to companies commercializing the inventions. From a certain viewpoint, this could be taken to mean that constraints had resulted to radical innovations.

However, as I have suggested in the case studies, the technological systems were largely poised for a change in any case, and the constraints gave the change simply some additional stimulus or helped to overcome barriers to change. As discussed in the Introduction, the poisedness for change came largely from “era of ferment” (Anderson & Tushman, 1990; Kaplan & Tripsas, 2008), or anticipation of alternative concepts by forward-thinking engineers and inventors, and were manifested in a number of experiments, analyses and patents appearing before the innovations were finally taken into use. The jet engine community of practitioners (Constant, 1980) were almost without doubt aware that higher turbine temperatures would be desirable, and that cooling the blades would be one way to achieve this; similarly, the metallurgical community was clearly aware of the potential benefits of burning sulfur ore and of oxygen injection, and it seems probable that most if not all competent metallurgists knew that the key of achieving energy-efficient smelting was the minimization of heat losses through flue gases.

Furthermore, the “radicalness” of these innovations is a matter of interpretation. Although undoubtedly ingenious, the core solutions in both cases were largely “ersatz” substitutes and were abandoned once alternatives were available. A similar dynamic that led — initially — to suboptimal solutions being adopted as a response to environmental regulation has been reported by (Yarime, 2007), and no doubt similar substitutions have happened elsewhere. The practical implication of this tendency for constraint-induced innovations to be inferior in quality is to cast some further doubt into the net benefits that can be achieved through innovation offsets.

Taken together with the research findings arguing that positive innovation effects require the proper timing of environmental regulation (Kemp & Pontoglio, 2011; Kivimaa, 2008; Sartorius & Zundel, 2005), the research also suggest the possibility that the connection between regulations and technological change may be more tenuous and indirect than research designs often allow. The alternative interpretation — a null hypothesis, if you will — that could explain the importance of timing is that in research that has found positive innovation effects, the technological system had been poised for a change anyway, while in the studies where no positive effects had been found the system had not been so poised. In this context, the poisedness may be understood as a situation where improved technologies and components have been developed and perhaps even taken into limited use, but they haven't been adopted by the majority of potential users. What the constraints (either regulatory or otherwise) then achieve is to, at most, spur the adoption of already developed technologies, not the development of novel technologies. This abstraction seems to concur with previous studies that have found that regulations tend to aid primarily the diffusion of innovations (e.g. (Christiansen, 2001; Mickwitz et al., 2008)). While both adoption and innovation result to technological change, from the innovation effects and innovation offsets point of view the latter is certainly more important.

The thesis of this paper, borne from the analysis of historical cases, is that innovation effects are real insofar as diffusion and adoption of innovations is concerned. However, the effect that constraints and henceforth regulation have on the development of cutting-edge, radical, *more productive* technologies is extremely limited: at most, it may accelerate otherwise likely or even unavoidable developments by a few years or so. Nevertheless, I have no wish to promote simplistic technological determinism. The innovations described in these case studies were contingent on a multitude of factors, technical possibility being only one of them. Without pressure and commitment created by the constraints, the hollow, sheet-metal turbine blades would probably not have been adopted, and Outokumpu would likely have continued the use of the electric furnace.

My conclusion therefore would agree with findings from a detailed case study reported by Roediger-Schluga (2004), who finds that at least in the short to medium term, environmental regulations have little impact, positive or negative, on innovation. However, the research so far leaves open and indeed suggests the possibility that environmental regulations and other constraints exert a positive influence to technological change, but that influence is more indirect and lags well behind the regulatory changes. This possibility of long-term benefits might be worth exploring in future studies, although difficulties in separating the influences over long time periods remain formidable.

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